Boeing Wichita
Human Factors

Human
Reaction
to Low
Frequency
Vibration

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Technical Report No. 1

HUMAN REACTION TO LOW FREQUENCY VIBRATION

Research Accomplished Under
Office of Naval Research
Contract Nonr 2994(00)
"Research On
Low Frequency Vibration Effects
On Human Performance"

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ABSTRACT

Systematically derived judgments of levels of vertical sinusoidal vibration severity from 1 to 27 cps were obtained under laboratory controlled conditions for each of 16 selected male subjects. These vibration levels were established in terms of four levels defined as Definitely Perceptible, Mildly Annoying, Extremely Annoying and Alarming as acceleration increased for each fixed frequency at a constant rate. The results established four profiles of acceleration from 1 to 27 cps to be used as the vibration frequency and amplitude points in the vibration environment for a series of tests of human performance in the remaining program. Correlation of judgment with velocity, acceleration, and double amplitude according to frequency were noted. A definite correlation between reported body area selectively affected and frequency was also found. As reported in previous studies in the literature, the body is evidently more sensitive to vibration at selected frequencies, suggesting body organ and appendage resonance.

Document Number D3-3512-1 reports the first experiment of a series designed to study vibration effects on human performance. Other experiments will be reported sequentially in the document series D3-3512-2 through D3-3512-7. All results will be integrated and summarized in D3-3512-0.

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Approved J. E. Beaupeurt
Unit Chief

Approved
Subsection Chief

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SUMMARY

This experiment was conducted in the Boeing Human Vibration Facility to derive vibration intensity judgments of (1) Definitely Perceptible, (2) Mildly Annoying, (3) Extremely Annoying, and (4) Alarming, in a descriptive range including a lower intensity of (0) Just Barely Perceptible, and higher intensities of (5) Limit of Physical Control, and (6) Limit of Voluntary Tolerance. Judgments were obtained for 16 frequencies in the range 1 to 27 cps, using 16 subjects who identified intensity by pressing a button under the right index finger. It was expected that intensities defined as (1), (2), (3), or (4) above would be used as the specific controlled vibration environment for studies of effects of vibration on human performance later in the program.

The data analysis indicated that the obtained intensity levels would satisfy vibration requirements for future studies in this series. It was discovered that the levels could be correlated with velocity, acceleration, and double amplitude, or combinations of these depending on different frequency ranges. Velocity was essentially constant at 1 to 1 1/2 cps, acceleration at 1 1/2 to 8 or 10 cps, double amplitude at 8 or 10 to 16 cps, and a combination of acceleration and double amplitude was most closely related to judgment levels from 16 to 27 cps.

Judgment of vibration varied significantly between levels and between frequencies (using acceleration to define intensity) suggesting distinctions related to judgment as well as frequency. Similar differences between subjects could not be explained since differences in semantic, personality (e.g., cautious attitude) and body characteristics were involved.

A distinct correlation between affected body area and frequency was discovered by tabulating subject and experimenter observations. Lower frequencies affect one part of the body more, with increasing frequency paralleling shifts to other body regions so that reports of affected body areas changed from "buttocks" to "abdominal", "chest", then to "vision and head". No reliable correlation trends could be found between affected body area, judgment of vibration, and body characteristics.

CONCLUSIONS AND RECOMMENDATIONS

I. VIBRATION LEVELS

A. Four levels of vibration described as (1) Definitely Perceptible, (2) Mildly Annoying, (3) Extremely Annoying, and (4) Alarming, were derived in this experiment.

B. These four levels will serve the intended purpose of identifying frequency and amplitude combinations for performance measures during later experiments.

1. There were wide variations between these vibration levels as frequency varied.

2. The data indicated that defining vibration test conditions simply in terms of constant acceleration or double amplitude as frequency varies is undesirable in certain regions if potential danger is to be avoided.

C. The levels of vibration derived in this study differ from much of the similar research which has been reported, particularly in a parallel increase of acceleration and frequency found from 8 to 15 cps. These differences appear to be related to test configurations and supports, and to orientation of the subjects.

II. CURVE ANALYSIS AND COMPARISONS

Summary Curves

A. Vibration judgment for given frequency ranges was related to constant velocity, acceleration, and double amplitude as follows:

Velocity	$\cong$	K, 1 to 1 1/2 cps
Acceleration	$\cong$	K, 1 1/2 to 8 or 10 cps
Double Amplitude	$\cong$	K, 8 or 10 to 16 and 18 cps
Double Amplitude vs. Acceleration	$\cong$	K, 16 and 18 to 27 cps

B. Relatively high acceleration sensitivity was indicated at 1, 4 to 10 and above 20 cps, with accepted accelerations notably lower for subjectively equivalent vibration.

Individual Curves

A. Apparent differences between vibration levels were statistically significant.

B. For the total frequency range, relatively high accelerations were derived for equivalent levels in the 1 1/2 and 18 cps regions. Exact occurrence of these accelerations varied in frequency for different subjects.

C. Curve trends were the same for all subjects.

III. CORRELATIONS

A. A definite correlation was found between frequency and affected body area. Reports of effects shifted from lower to upper thoracic-abdominal regions, then to the head as frequency increased.

B. Vibration effects on the extremities shifted from general to localized as frequency increased.

C. No correlation could be found between gross body characteristics and vibration judgments.

D. Relatively minor control of diet, elimination, and rest appeared to be sufficient. No discrepancies in results related to the relatively minor subject variation in these controls were discovered.

IV. APPLICATION OF DATA

A. The curves of vibration intensity derived indicate operable levels of vibration for short time periods. At this time it is not considered desirable to exceed the highest intensity levels with random vibration peaks on more than an occasional basis. Even then, caution is particularly desirable in considering level 4 in the region 3 to 8 cps. More conservative recommendations may become necessary as performance information related to these curves becomes available later in this program.

B. The nature of the vibration curves suggest that vibration may be dissipated by conversion to less troublesome frequencies through structural design or modification.

C. Data from reports by the subjects suggest body regions which are affected and which can be used to analyze frequency-acceleration effects on specific human task functions integrated into a total job for an interim approach in system design pending data from later studies in this program.

V. REQUIRED STUDIES

A. A literature review and integration primarily intended as a design handbook is required. Division of the review into three major sections of information is recommended: (1) Human Engineering, (2) Psychological, and (3) Physiological.

B. Experiments and analyses are required to determine correlates for extrapolating psychological and physiological data from sinusoidal to random operational environments.

C. Effects of long time exposure to sinusoidal and random vibration require study.

D. General

1. More precise systems for scaling psychological responses and body reaction to vibration are necessary to aid in understanding discrepancies between studies and to establish the best descriptions of human response to vibration.

2. Knowledge of mechanics of body organ response, through definition of displacement and spring-mass relationships of body organs and supporting tissues is necessary.

3. Specific studies to identify appropriate restraint and support systems are required.

E. A program is recommended to determine effects of vibration related to variations in body type, age, experience, weight, sex, temperature and humidity.

INTRODUCTION

There is considerable evidence that vibration affects human performance (References A, K, L, and O), but little information directly applicable to design problems is available. As a result, vibration found in low altitude flight vehicles and expected in re-entry of space capsules into the atmosphere as well as vibration from other environments have emphasized the need for human vibration data applicable to operational systems in designing optimum man-machine systems. Data is available for descriptions of (1) comfort, (2) physiological effects, and (3) human judgment of vibration. However, reported performance information is limited for use in solving practical design questions about expected human performance during system vibration. Most available data has been obtained for comfort and physiological studies or highly specialized performance requirements such as visual acuity and simple tracking problems that are too remote from the problem for many design questions.

This experiment is the first of a series designed to study effects of vibration on human performance specifically for a broad range of human skills as they are to be applied in current and future systems. The study reported here was designed to systematically derive judgments of vibration intensities in the range 1 - 27 cps under carefully controlled conditions for a description of psychological responses to the effects of vibration on the body. The levels of vibration defined by this method will be used to specify intensities in the rest of the study within limits of physical control by human subjects.

Several purposes were included in planning for this study. The levels to be obtained were expected to permit correlation of judgment with physical descriptions of vibration (velocity, acceleration, double amplitude and frequency). Interview questions concerned with general comments and affected body area were designed to obtain information for relating physical descriptions of vibration, judgment, and body characteristics. Subjects' suggestions were collected for possible problem areas requiring immediate study for current systems, and for improved program procedures, as subjects and experimenter obtained a better understanding of what to expect with vibration.

This experiment was designed to define vibration intensities to provide an operational framework for later studies. In later studies data will be collected for direct application in systems design, including the effects of vibration on: hearing and speech; visual acuity and movement perception; linear and rotary movement of the fingers, and of the hand and arm; a complex task involving all of these; and foot response capability. This data will be integrated in a summary report to provide information for the following:

1. Vibration affecting specific perceptual-motor skill requirements within a range of 1 - 27 cps.

2. Perceptual-motor abilities affected by vibration and the frequency-amplitude combinations related to these effects.

3. Limitations in applying data to design problems.

4. Requirements for display control design with low frequency vibration.

5. Expected individual variability for specific perceptual-motor skills during vibration, and

6. Information for improving human performance during vibration for improved systems capabilities.

Experience has shown that this information coupled with task performance data broadly representing human capability is necessary to meet design engineering requirements.

To obtain background for this study, a selected list of references was reviewed and analyzed for determining vibration effects on humans, questionable vibration intensities and general background. A summary of comparable data collected from these reviews is shown graphically in figures 1 and 2, with figure 1 indicating judgment and tolerance data (including data from this experiment) and figure 2 presenting intensities used in collecting performance data.

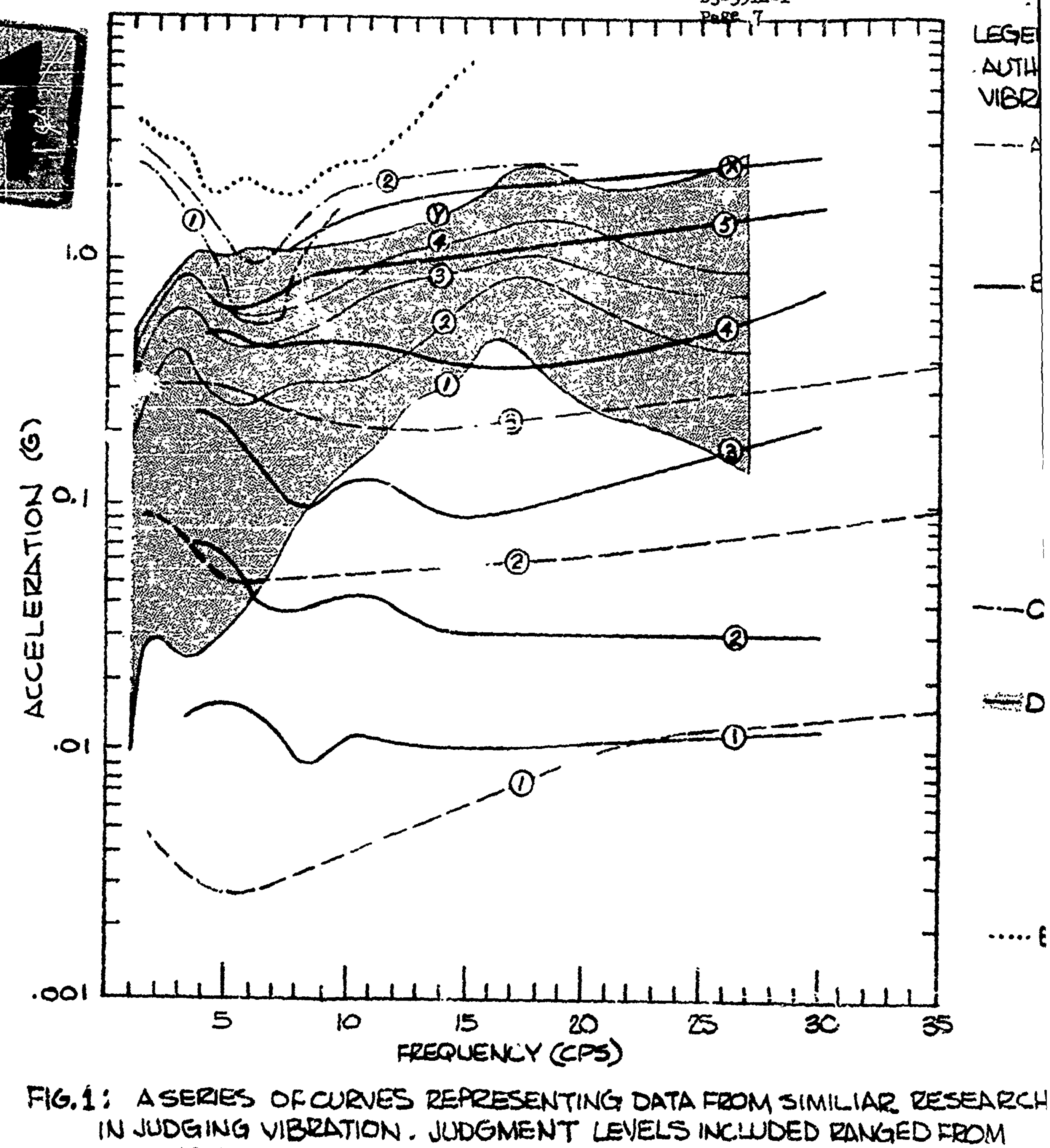
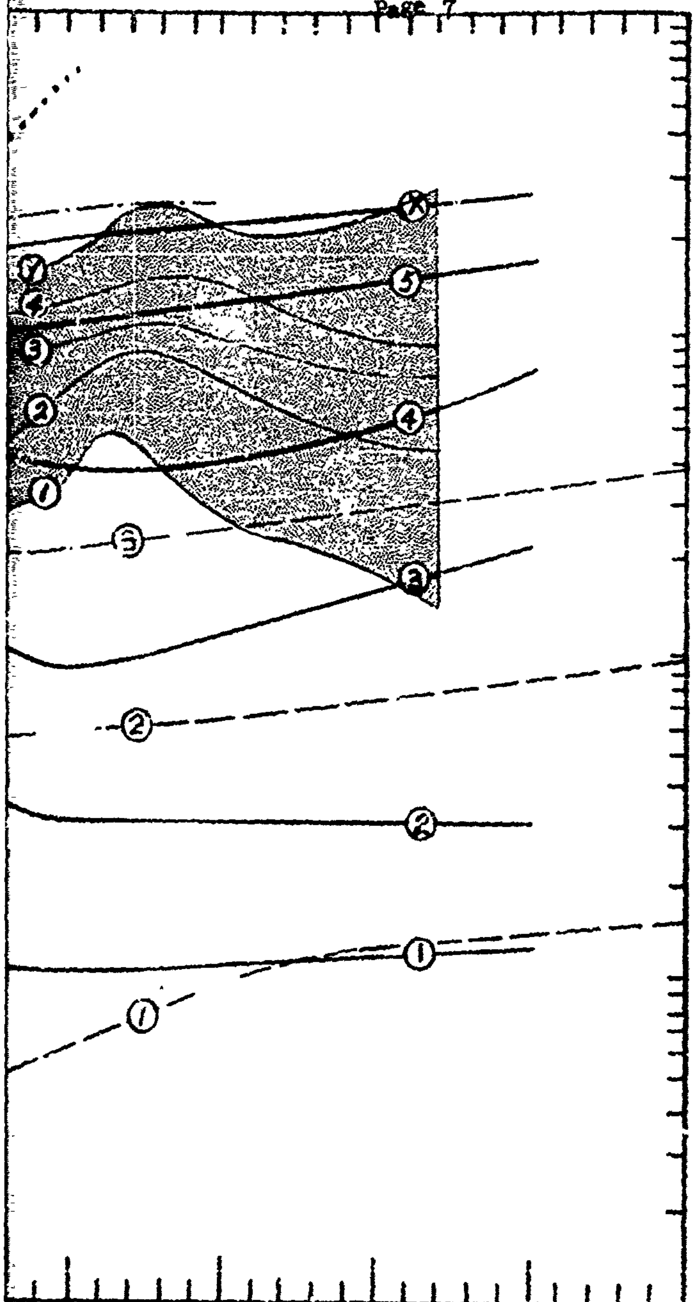


FIG. 1: A SERIES OF CURVES REPRESENTING DATA FROM SIMILIAR RESEARCH IN JUDGING VIBRATION. JUDGMENT LEVELS INCLUDED RANGED FROM THRESHOLD OF PERCEPTION TO THE LIMIT OF ACCELERATION SUBJECTS "WOU BE WILLING TO UNDERGO BEFORE IT WAS THOUGHT THAT ACTUAL BODY HARM WOULD OCCUR". DATA FROM THIS REPORT IS INCLUDED FOR COMPARISON.



LEGEND
AUTHORS & DESCRIPTION OF VIBRATION.

— — A. GOLDMAN (REF. F)
1. PERCEPTABLE
2. UNPLEASANT
3. INTOLERABLE

—— B. GORRILL & SNYDER (REF. A)
1. THRESHOLD OF PERCEPTION
2. DEFINITELY OR EASILY PERCEPTIBLE.
3. IRRITATING OR ANNOYING
4. MAX. TOLERABLE FOR CONTINUOUS OPERATION
5. INTOLERABLE.
X HIGHEST INTENSITY ENDURED

—·— C. MAGID & COERMANN (REF L)
1. THREE MIN. TOLERANCE LIM.
2. ONE MIN. TOLERANCE LIM.

D. PARKS
1 DEFINITELY PERCEPTABLE
2 MILDLY ANNOYING
3 EXTREMELY ANNOYING
4 ALARMING
Y HIGHEST INTENSITY CALLED ALARMING

····· E. ZEIGENRUECKER & MAGID (REF. P)
1. SHORT TIME TOLERANCE

REPRESENTING DATA FROM SIMILIAR RESEARCH
JUDGMENT LEVELS INCLUDED RANGED FROM
N TO THE LIMIT OF ACCELERATION SUBJECTS "WOULD
BEFORE IT WAS THOUGHT THAT ACTUAL BODY HARM
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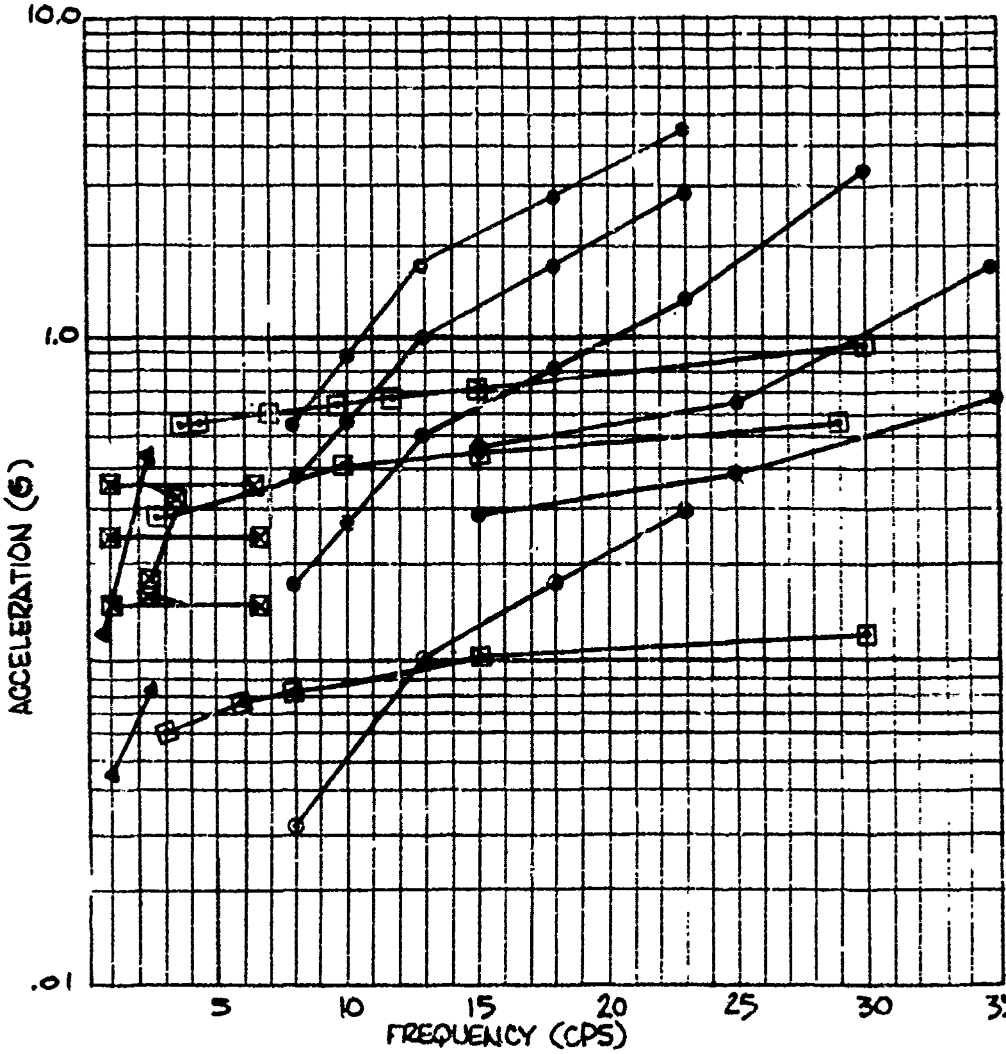


LEGEND: ⊡ REF. A - GORRILL & SNYDER
▲ REF. C - D. PARKS
◎ REF. M - MOZELL & WHITE
● REF. K - M. LOEB
⊠ REF. N - SCHMITZ, SIMMONS & BOETTCHER.

FIGURE 2: SUMMARY OF VIBRATION ACCELERATIONS USED IN SELECTED STUDIES OF HUMAN PERFORMANCE.

METHODOLOGY

Apparatus

The Boeing Human Vibration Facility (Reference B) was used to provide the vibration environment for this test: a vertical, sinusoidal vibration with a very gradual increase in amplitude at each frequency used in the range from 1 - 27 cps. A standard aircraft seat was reinforced (to insure the most complete transmission of vibration possible) and mounted to the platform. Reinforced plywood inserts covered with 3/4 inch hard felt were used in place of normal seat cushion or parachute packs to insure full transmission of vibration through the chair to the man so that all subjects would receive the same regulated vibration input at the point of contact with the seat. This averted problems associated with a complex seat absorption pattern or with different subject weights (Reference A, p 17), and allowed for a better comparison between subjects than might otherwise be possible.

A heavy aircraft control wheel and column were installed in the normal operating position with respect to the subject for these tests. Subjects (Ss) were required to hold a "deadman" switch located under the left hand fingers on the wheel throughout each vibration period. A signal button on the right hand grasp and adjacent to the index finger was used to record the levels of vibration.

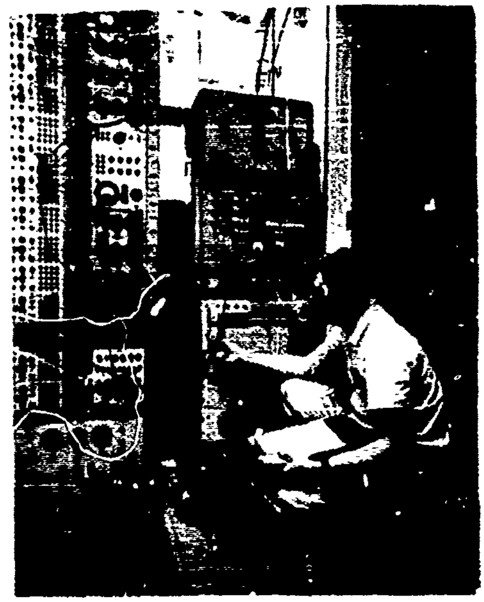
A test display panel was mounted to the platform and in front of the control column, located about 28" in front of the subject. The center of the display was perpendicular to a line of sight dropped 10° from the horizontal. While it was not part of this test, the subjects practiced on the task (Reference C) between vibration periods in preparation for a later experiment.

Vibration

A signal generator was used to control vibration frequency. The generator set at a given frequency, controlled the period by operating a servo-actuated ram-lock system. A linear feedback potentiometer on the platform fed a signal back to the control unit which insured control of vibration amplitude according to specifications.

The experimental procedure was to gradually increase amplitude from 0.0 for each frequency tested, with S indicating each level as he judged amplitude had reached each defined intensity level.

A. VIBRATION TEST CHAMBER



B. EQUIPMENT CONTROL CENTER

C. EXPERIMENTAL CONTROL STATION

FIGURE 3: TEST STATIONS MANNED DURING TESTING. AN M.D. WAS ALSO PRESENT AT THE EXPERIMENTAL CONTROL STATION.

Frequencies

The frequencies selected for testing in this study were 1, 1 1/2, 2, 3, 4, 5, 6, 8, 10, 12, 14, 16, 18, 20, 23, and 27 cps. These were divided into two groups for the two groups of subjects who were tested as follows:

Group A	1,	1 1/2	2,	4,	6,	10,	14,	18,	23
Group B		1 1/2	3,	5,	8,	12,	16,	18,	20, 27

This organization of groups and frequencies would permit some over-lapping between groups to check comparability and avoid an extensive test period requiring all subjects to evaluate all frequencies, while permitting reasonable coverage of the frequency range to be investigated.

Electrocardiograph (ECG) Recordings

An electrocardiograph system was developed to permit monitoring of each Ss condition during testing. It consisted of three wire mesh contacts, two on the pectoral muscles of the chest and one (a ground lead) on the right mastoid process. These were prepared by rubbing the body area and the contact with an electrolytic jelly commonly used for ECG contacts. The two pectoral contacts were held in place by elastic bandages, the mastoid contact with collodion (a kind of glue used by M.D.'s to protect wounds). This system was then plugged into a vibration seat terminal where the signal was transmitted and magnified by a D.C. amplifier for a print-out on a two-channel brush recorder. While somewhat subject to muscular excitation, the system would give a perfect ECG record at best, and heart beat strength and rhythm at worst.

Judgment Levels - Rationale

As was indicated in figure 1, few research efforts agreed in defining vibration intensity, with "Tolerance Limits" for one study exceeded by another's implication of "Mildly Irritating". Goals of the studies differed but semantic and other individual differences are also suspected. For example: One study would be interested in the maximum intensity fare-paying passengers would accept, another in the point where damage was imminent.

To avoid these problems several analytical approaches to defining judgment levels for vibration were tried, including the more precise techniques developed by Thurstone (Reference C) and those of deriving a scale of Noticeable Differences. Many psychological dimensions (pain, fear, physiological, general perception and others were noted) lead to the conclusion that an extensive program and considerable direct experience by judges in perception of vibration was necessary to use more precise judgment procedures. Alternate solutions were attempted since an extensive effort to develop a human vibration scale was outside the scope of this program.

An analysis to define vibration very precisely was rejected as experience again became an obvious requirement and as it became apparent that too rigid a definition could force subjects into intensity regions that they could not accept.

The final exercise resulted in a decision to permit semantic and individual fluctuations according to the subjects' interpretation, then provide individual subject and summary descriptions of judgment levels to define an acceptable range of vibration for the rest of the program. This would provide concrete points for testing and permit understanding of the range actually descri ed by the particular levels.

Subjects (Ss)

Subjects were 17 Boeing Wichita employees who volunteered for the studies in response to a notification to test aircraft operators and a company newspaper article indicating that volunteers were needed. Volunteers were interviewed by the experimenter, then required to undergo a comprehensive physical examination as part of the pretest procedure (which eliminated 50% of the volunteers). Several of the volunteers withdrew for reasons unrelated to the test.

The test started with 17 subjects, split into two groups of 8 and 9 subjects each. One S transferred and another terminated shortly after the test started. Unknown to the experimenter until the final test session, one S refused to accept the test framework because of what he termed "ambiguous levels". He had apparently developed his own scale which might be defined in part as four levels of "just discriminable" differences. His four levels clustered closest to the Definitely Perceptible levels of the other Ss. Unfortunately, while data and comments suggested during the experiment that this S might not be operating within the proper framework (Example: inconsistent reports "That fourth level wasn't alarming to me", followed by "I would consider it alarming") no positive indication of deviation from the defined levels could be determined until the final interview. Lack of understandable meaning or comparability of his data with the other Ss caused it to be discarded. The net result was seven Ss in Group A and nine in Group B, since one subject participated as a member of both test groups.

Test Procedure

Reference D movie describes all test procedures in detail. Ss wore flight coveralls, athletic supports, street shoes, and light gloves to the test preparation area. A medical examination was completed, after which the experimenter (E) questioned S briefly on condition, activity, and additional post test observations from the last session. E read instructions (Appendix A) to S and checked to make sure that they were understood.

All test personnel then assumed their test stations. A communication and preparedness check was completed, S was informed that he had about 30 seconds before the test started, and the ECG system was started for a pre-vibration record. At the end of 30 seconds for a non-vibrating base ECG, the vibration onset apparatus was started. S then identified the four levels as the amplitude onset continued.

Ss identified the four levels for three frequencies on each test day. For the first two frequencies vibration was stopped by S releasing the cut off switch after identifying the fourth level, "Alarming". For the third frequency S held the switch down, the vibration onset rate was reversed immediately after the fourth level was reached, and S identified levels 3, 2, 1 in that order as vibration amplitude decreased to zero. Some of this data was lost because Ss inadvertently released the switch after defining the fourth level.

The ECG recording continued for 30 seconds after each test frequency. After this the experimenter (E) would enter the vibration chamber and record S's general comments on bodily response to the frequency. At the end of 2.5 minutes, E would return to his station and coordinate the test for the next frequency. At the end of the third test for the day, this procedure was changed with S first being taken to the preparation area for an immediate post-vibration physical exam, after which comments on the third frequency were collected along with general comments on the test session.

RESULTS

Results and analyses for this experiment are summarized in figures 4 through 14 and in Tables I through III. Data has been organized to include all test information for data analysis via graphical, tabular, and statistical methods. Summary curves (figures 4 and 5) based on a mean, best fit, smooth curve indicate group trends and general relationships. Additional curves (figures 6 - 14) show individual variability for each level with statistical analysis of variability and differences included in Table II. The range of subject variability for the four levels of this test is shown in Figure 14. It is suspected that similar variability occurred for most research conducted in the past which records data simply as a mean, or as a mean and standard deviation (suggested from data and comments of References A, F, O). A summary of subject and experimenter observations appear in Table III, and raw data for each subject has been plotted in Appendix B.

Figures 1, 4 and 5 present this data on different coordinate systems so that all graphical systems used in reporting other research on vibration judgment are included and direct comparison of research efforts can be accomplished as necessary.

Figure 4 illustrates correlations between physical characteristics of vibration and human judgment. The special log coordinate system relates vector velocity in inches second (V), vector acceleration (G), double amplitude (A) and sinusoidal frequency (F) through the equations $G = .0511\ F^2A$ and $G = .0163\ FV$. Table I summarizes these and shows the correlation of each with judgment for given frequency ranges. An additional relation for jerk ($= 8\ \pi^3\ F^3A$) or rate of change (Reference H) in vibration acceleration is shown by one line only to avoid excessive confusion in interpreting the system.

TABLE I

Summary of Judgment Correlations As a Function of Frequency
(from Figure 4 Page 16)

All Levels	V [illegible] K	For	1, 1 1/2 cps
Level 1	G [illegible] K	For	2 to 5 cps
Level 2	G [illegible] K	For	2 to 8 cps
Levels 3,4	G [illegible] K	For	2 to 8 or 10 cps
Level 1	A [illegible] K	For	5 to 16 cps
Level 2	A [illegible] K	For	8 or 10 to 16 cps
Levels 3, 4	V [illegible] K	For	8 or 10 to 16 cps
All Levels	A vs G [illegible] K	For	16 - 27 cps

Figure 5 includes the same information, plotted as a function of G vs frequency to illustrate frequencies at which the body is G sensitive. Restrictions on this data and suspected for other vibration research data are suggested in figures 6 through 14, which include all individual variability for each level. This information is included to illustrate S variability and the reason for the belief that body type is important in judging vibration.

Ss tended toward more (apparent) violent movement of extremities, regardless of relative weight. However, the alarming level involved highest accelerations for a cross section of Ss, with size and weight as follows: 6'1", 192 1/2 lbs; 5'9 1/2", 156 lbs; 5'7 1/2", 173 lbs; 5'7", 172 lbs. No correlation could be determined for body characteristics and frequency or amplitude.

Inspection of the data curves may appear to provide sufficient certainty for the indicated data trends. However, only by using statistical techniques, such as are summarized in Table II, (Page 29) can it be determined whether differences are due to chance and normal fluctuations or related to some real difference in tested conditions. For these tests the 5 per cent level of confidence commonly used was considered sufficient to determine whether real differences occurred. In other words, when the mathematical probability was that the obtained differences would occur by chance 5 times or less in 100, it was accepted that a real difference was recorded.

Group differences suggested by graphical comparison are shown to be significant in Table II. Several factors could be contributing to these differences including Ss variability, different M.D. monitor for the two groups, or the fact that Group A finished the series prior to Group B starting (so that B Group knew that there had been no problems and could have been less conservative as a result).

Differences between Ss within each group were also indicated, with some Ss in both Group A and Group B differing significantly from others. However, the statistical test shows that levels are distinct even with the wide individual variability, and that judgment levels varied significantly according to frequency. Significant interactions (from Table II) of frequency and Ss, and levels and subjects, suggest that both frequency and factors related to displacement such as amplitude, velocity and acceleration were affecting judgment of vibration by Ss.

Data on S and E observations of affected body area and functions are presented as a scattergram in Table III. Reports of affected body area vs frequency emphasized a shift in effect which occurred as frequency increased. Reports shifted from the lower to upper thoracic abdominal area then to the head and related organs with increasing frequency. A similar result occurred with the extremities, with tendencies for the effect to become more localized with increasing frequency.

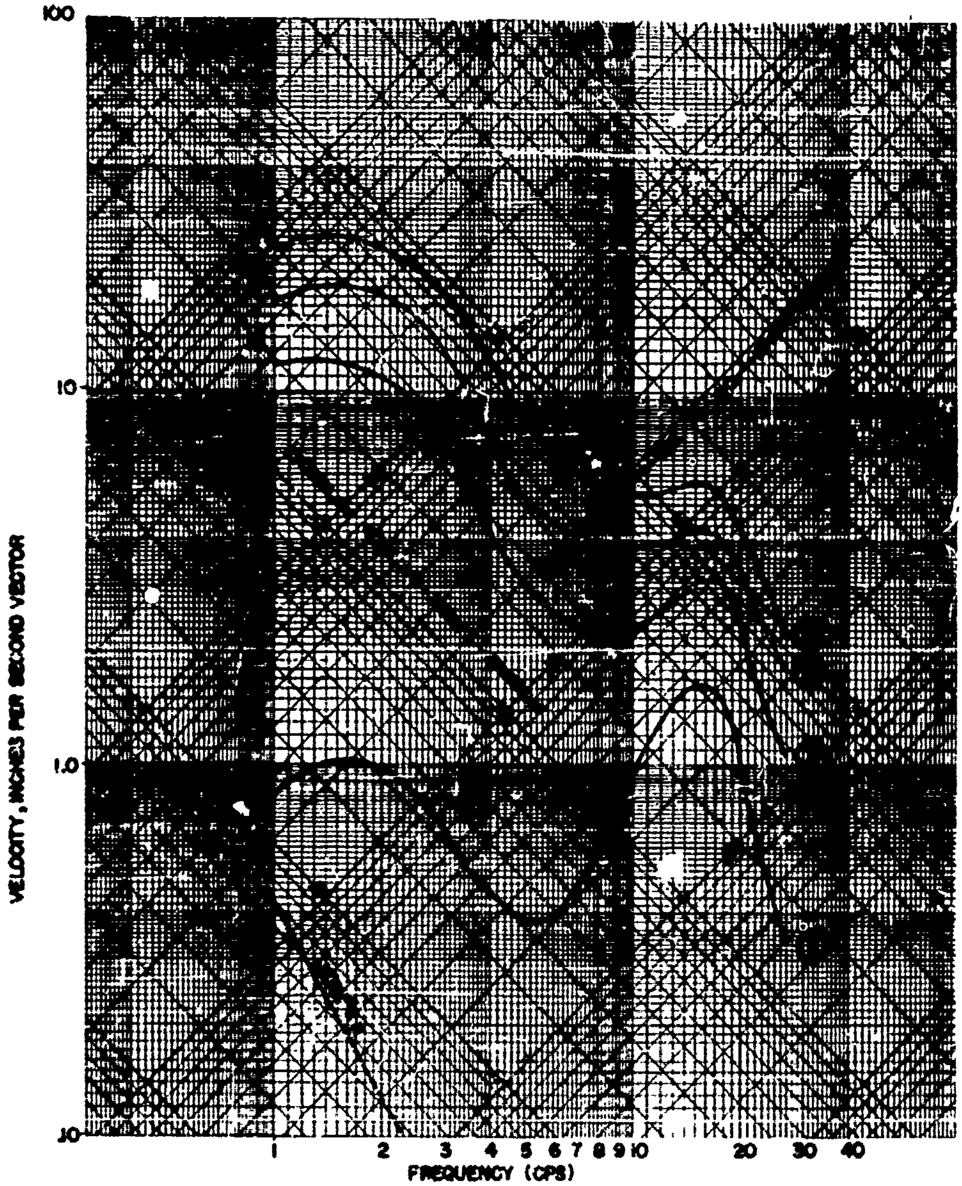


FIGURE 4: A SUMMARY OF DATA FOR JUDGMENT LEVELS 1, 2, 3 and 4. THIS COORDINATE SYSTEM PRESENTS THE MAJOR PHYSICAL DESCRIPTIONS OF VIBRATION, INCLUDING AN INDICATION OF THE RELATION THAT JERK HAS TO THE SYSTEM.

1. DEFINITELY PERCEPTIBLE
2. MILDLY ANNOYING
3. EXTREMELY ANNOYING
4. ALARMING

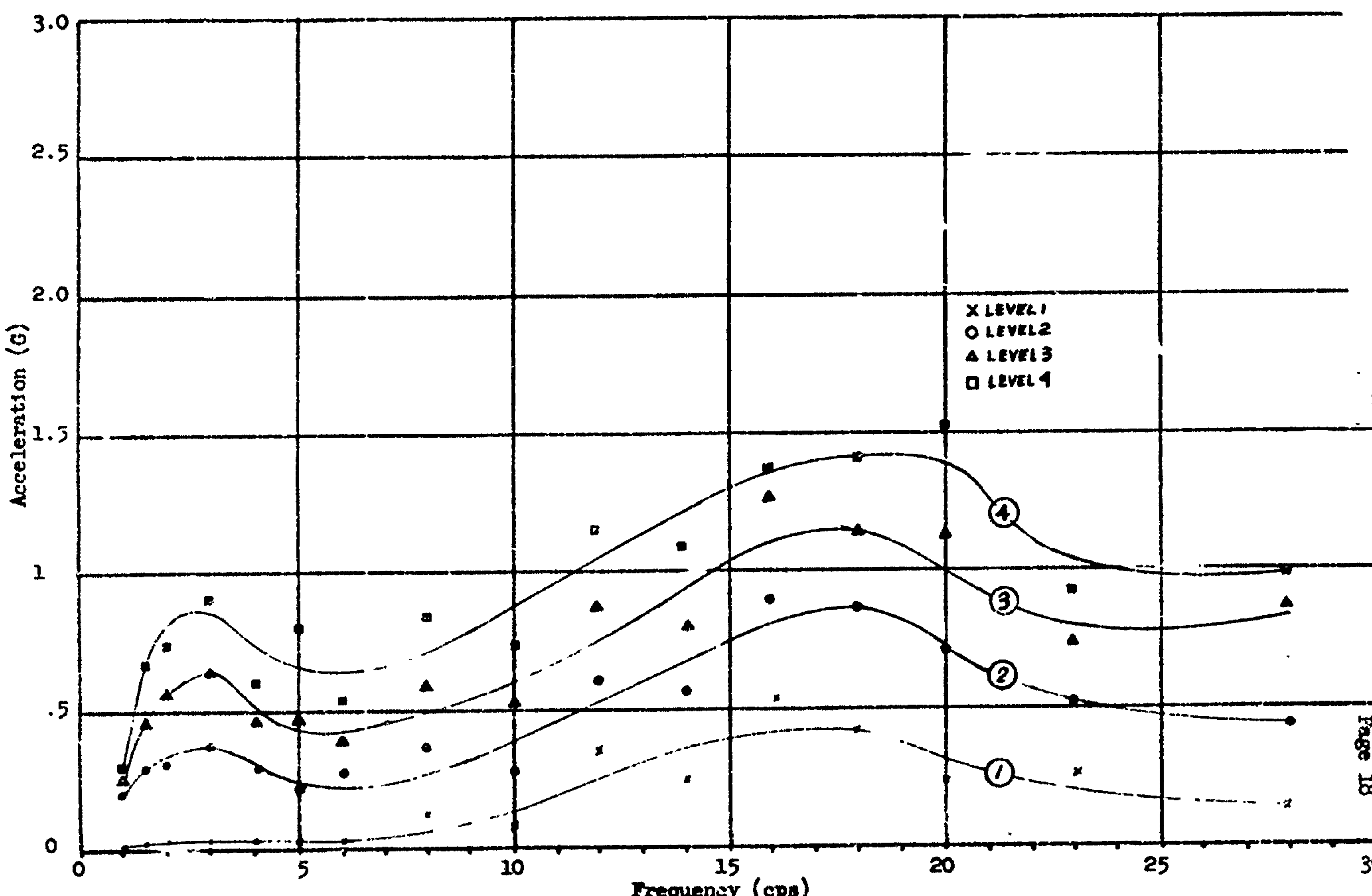


FIGURE 5: A SUMMARY OF DATA FOR JUDGMENT LEVELS 1, 2, 3, and 4, PRESENTED ON A LINEAR COORDINATE SYSTEM, "G" VS. CPS

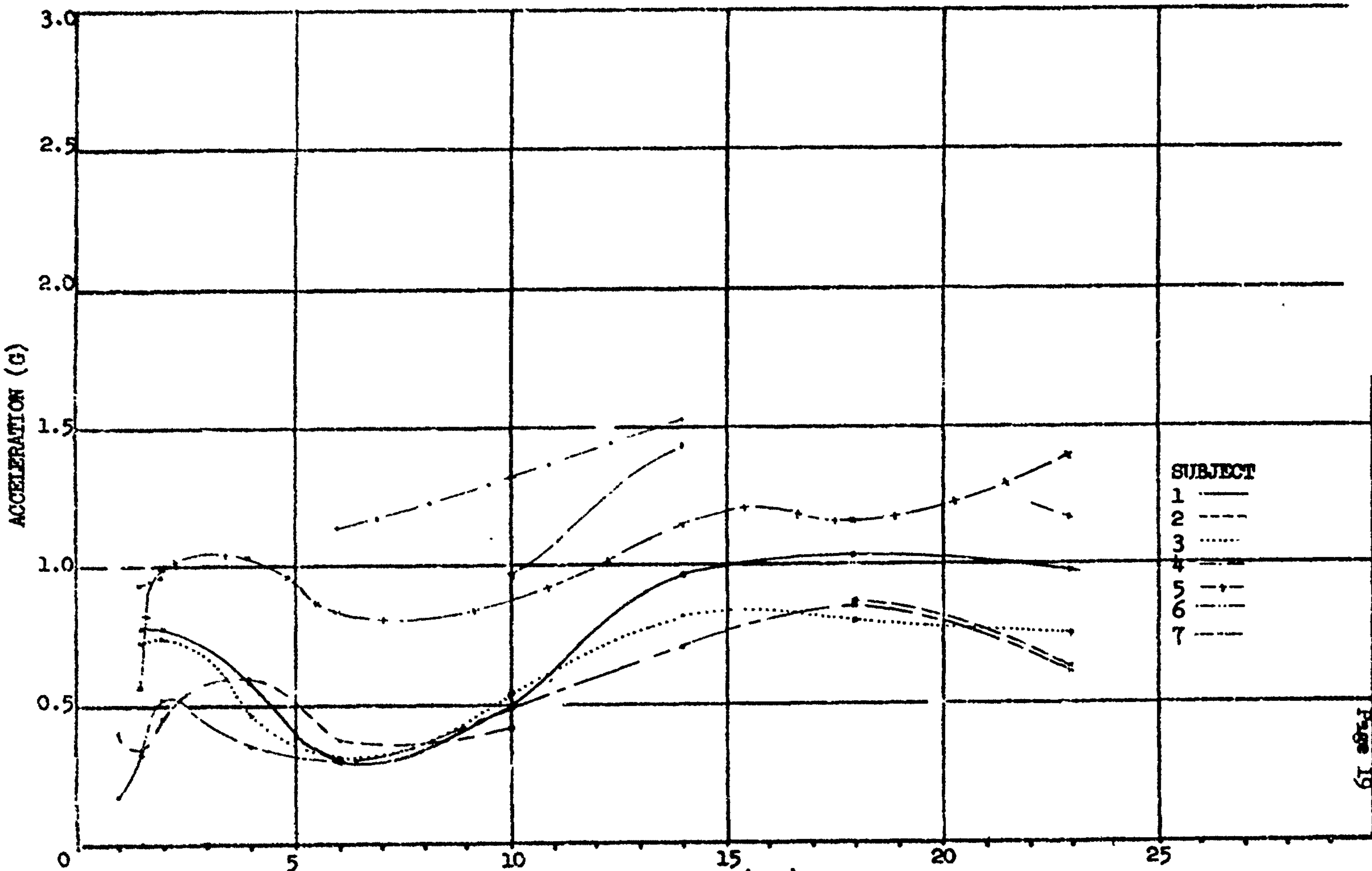


FIGURE 6: LEVEL 4, ALARMING, AS DEFINED BY 7 GROUP A SUBJECTS

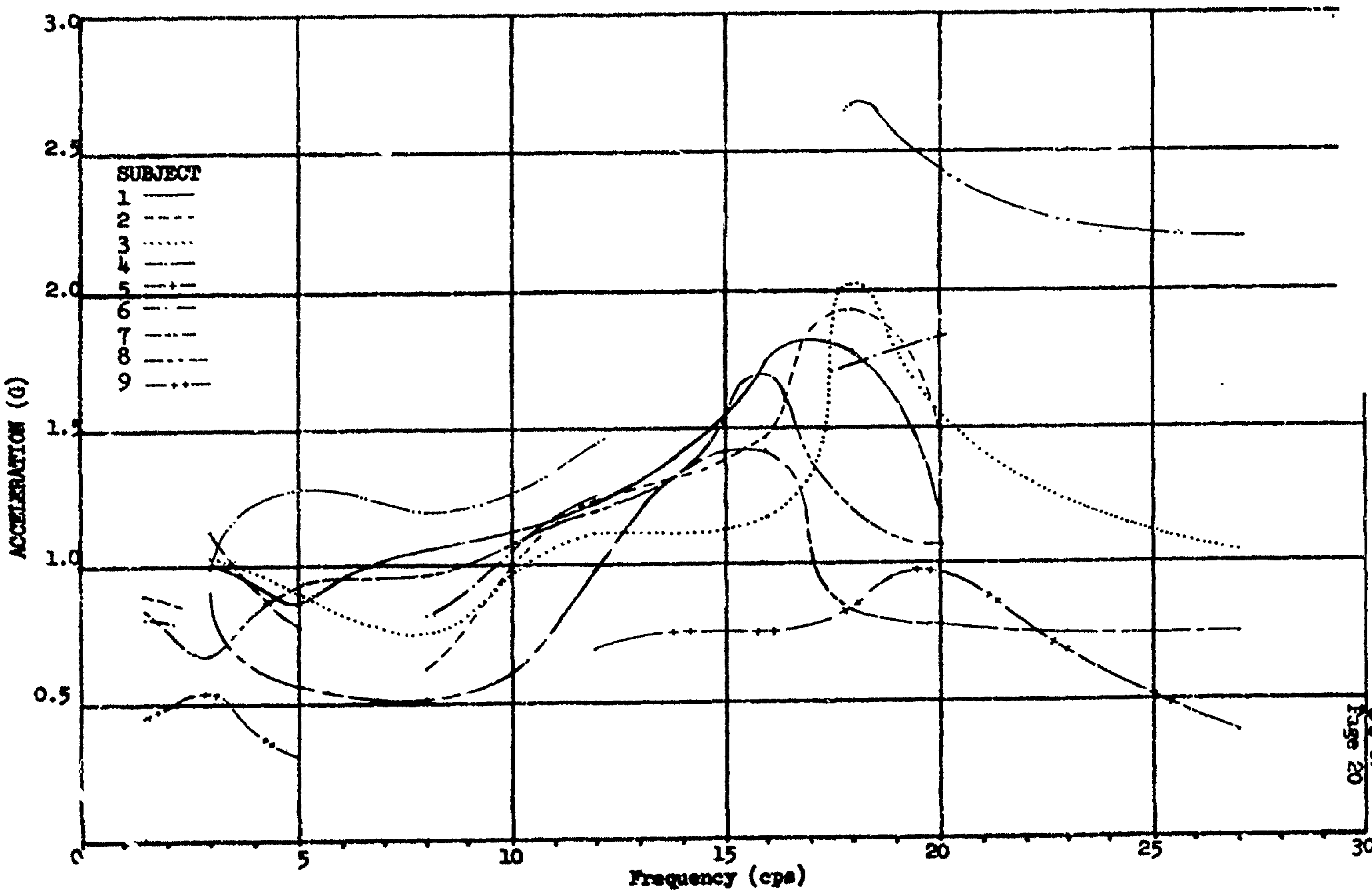


FIGURE 7: LEVEL 4, ALARMING, AS DEFINED BY 9 GROUP B SUBJECTS.

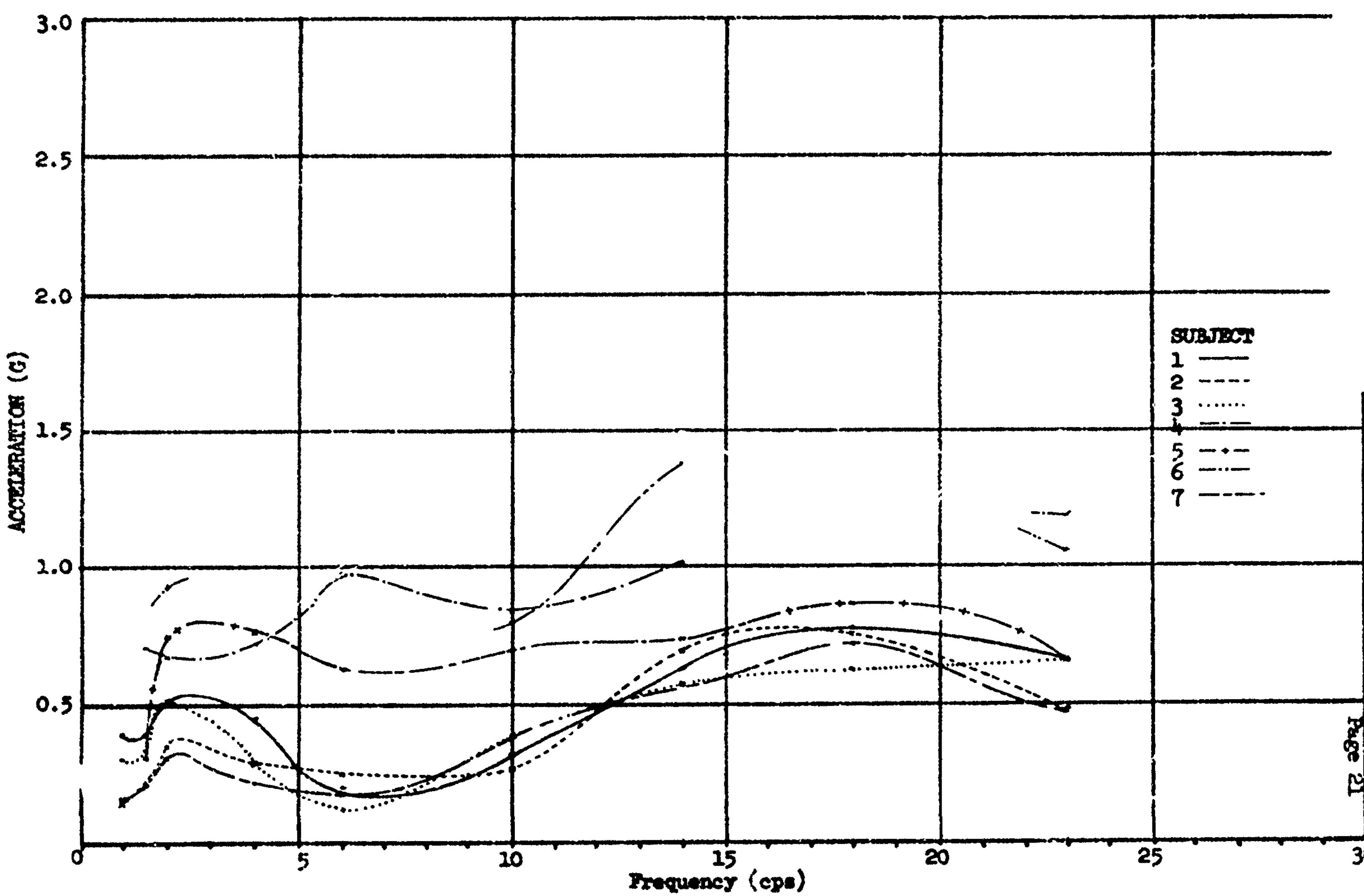


FIGURE 8: LEVEL 3, EXTREMELY ANNOYING, AS DEFINED BY 7 GROUP A SUBJECTS.

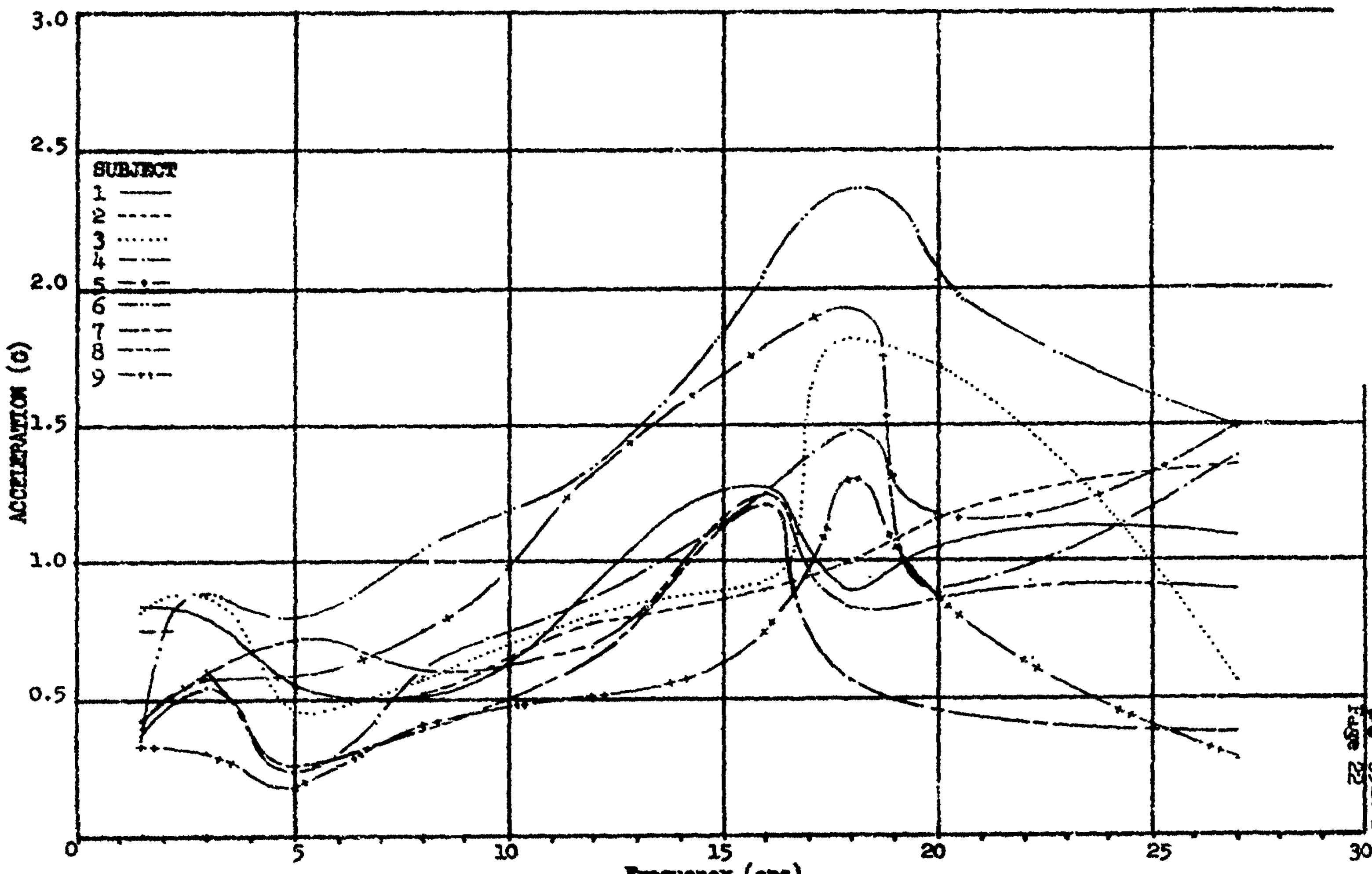


FIGURE 9: LEVEL 3, EXTREMELY ANNOYING, AS DEFINED BY 9 GROUP B SUBJECTS.

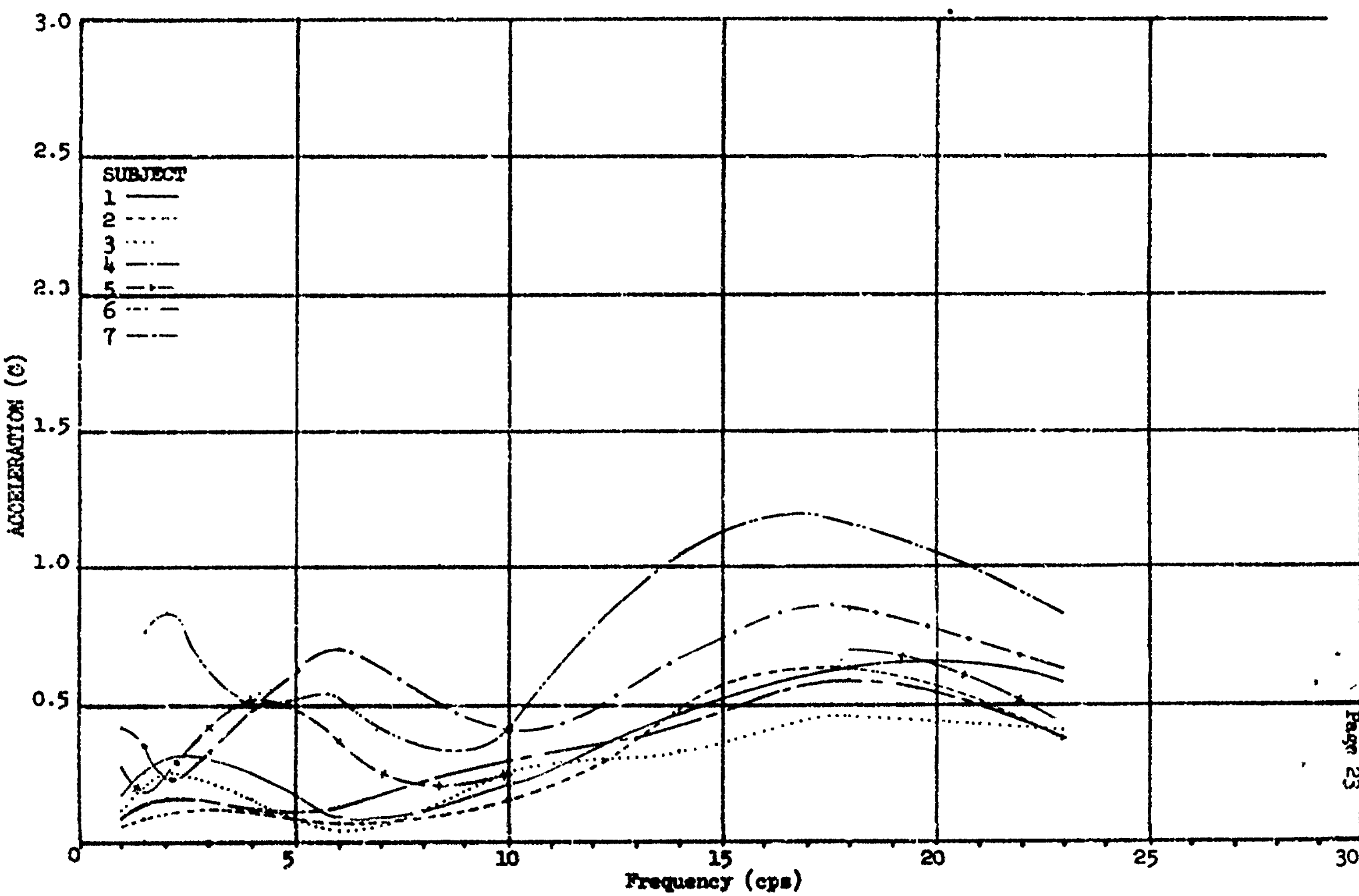


FIGURE 10: LEVEL 2, MILDLY ANNOYING, AS DEFINED BY 7 GROUP A SUBJECTS.

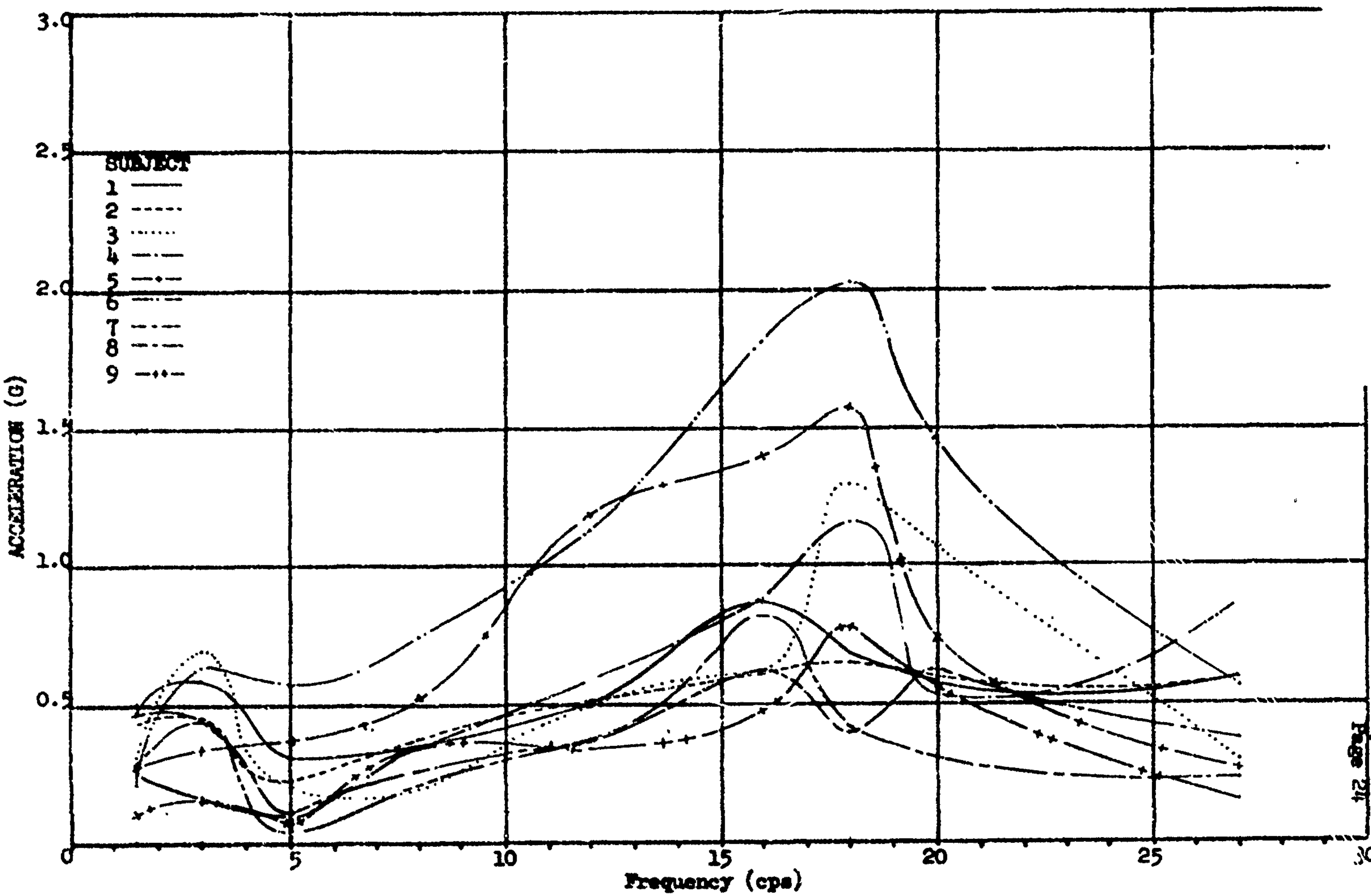


FIGURE 11: LEVEL 2, MILDLY ANNOYING, AS DEFINED BY 9 GROUP B SUBJECTS.

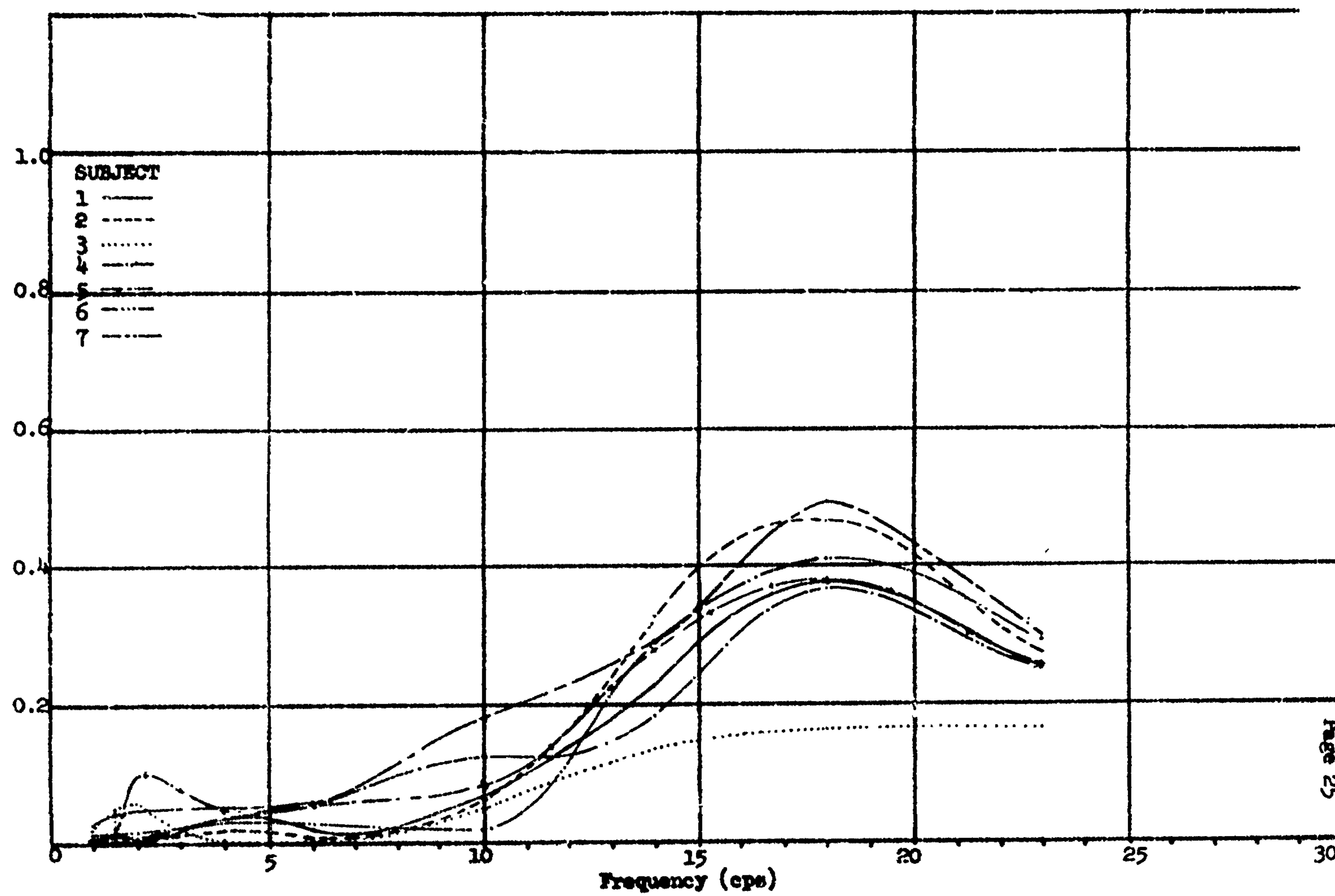


FIGURE 12: LEVEL 1, DEFINITELY PERCEPTIBLE, AS DEFINED BY 7 GROUP A SUBJECTS
(SCALE IS CHANGED FROM THAT OF FIGURE 6 to 11) NOTE: SCALE CHANGE ON THE ORDINATE)

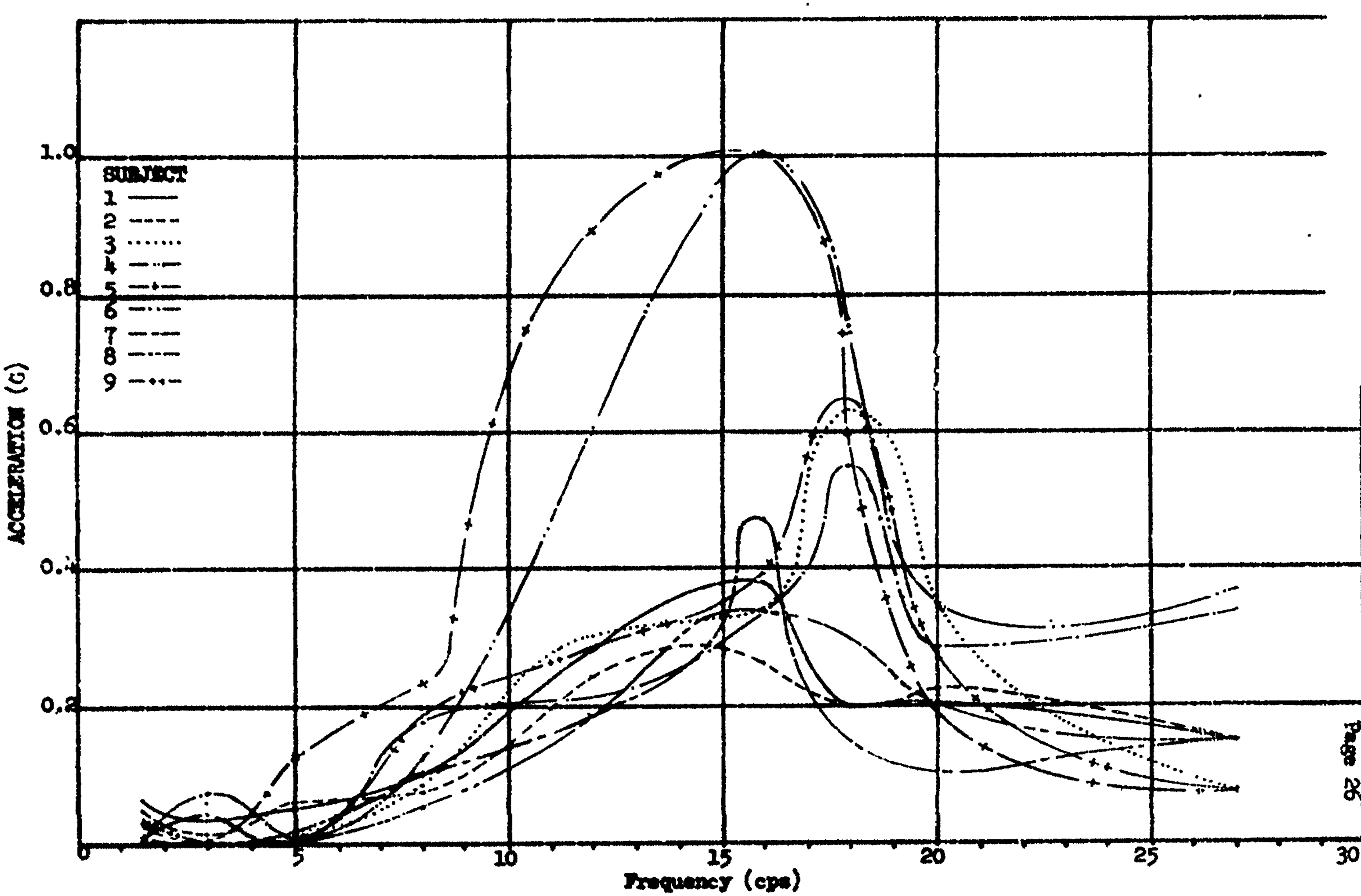
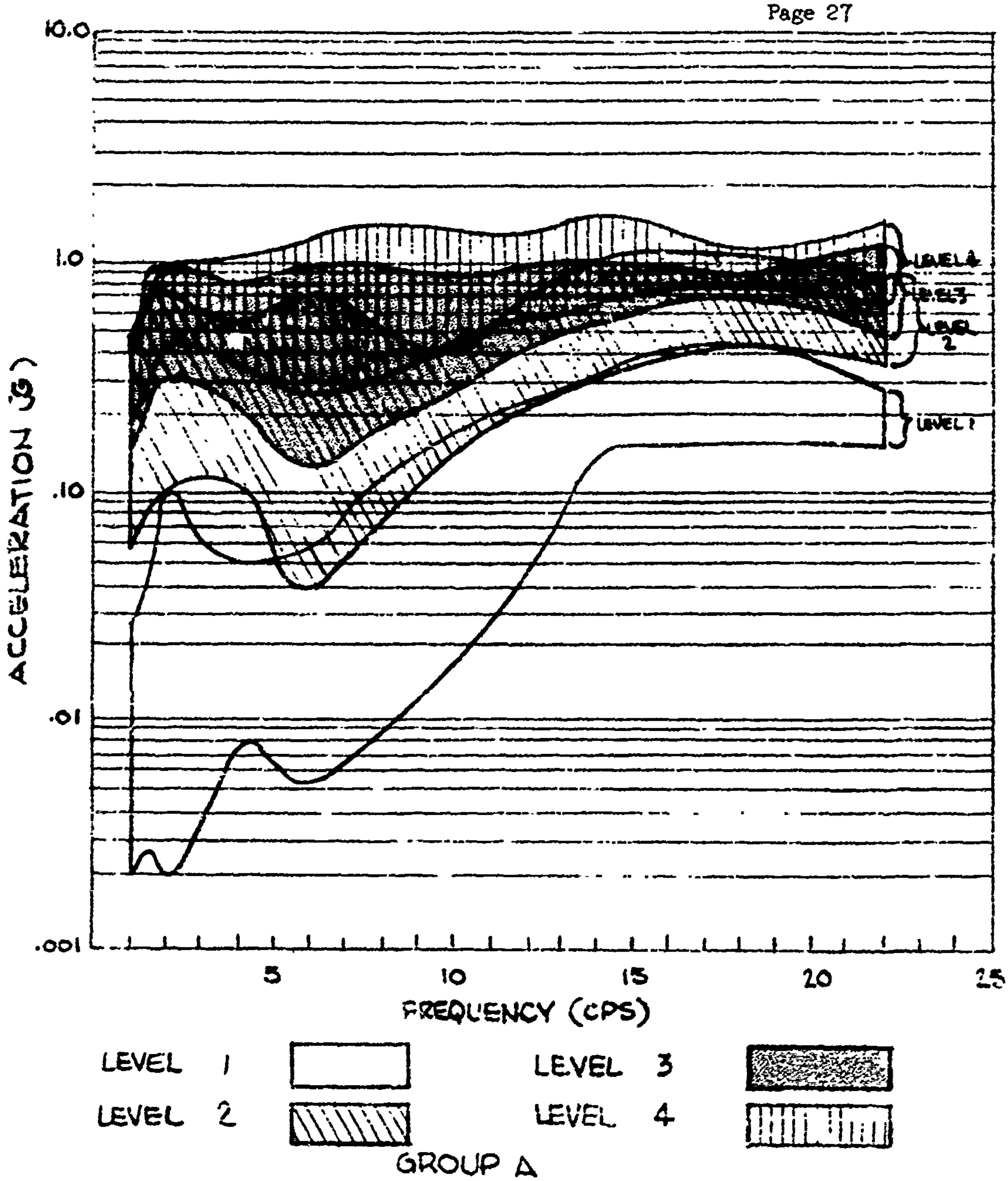
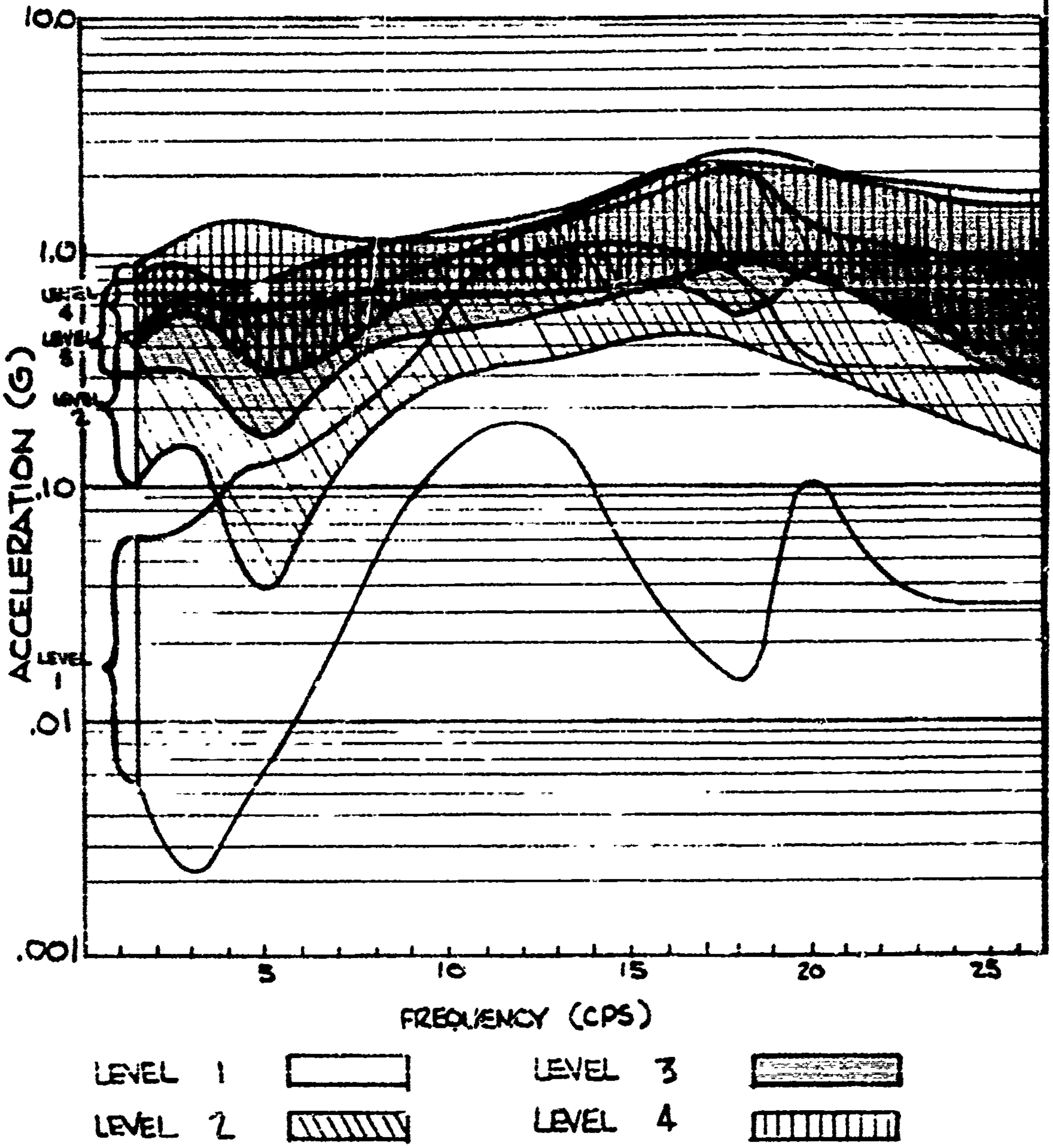


FIGURE 13: LEVEL 1, DEFINITELY PERCEPTIBLE, AS DEFINED BY 9 GROUP B SUBJECTS (SCALE IS CHANGED FROM THAT OF FIGURES 6 TO 11) NOTE: SCALE CHANGES ON THE ORDINATE



GROUP A

FIGURE 14a: SUMMARY OF 4 VIBRATION LEVELS FOR GROUP A, ILLUSTRATING OVERLAP BETWEEN LEVELS RESULTING FROM INDIVIDUAL DIFFERENCES.



GROUP B

FIGURE 14B: SUMMARY OF 4 VIBRATION LEVELS FOR GROUP B, ILLUSTRATING OVERLAP BETWEEN LEVELS RESULTING FROM INDIVIDUAL DIFFERENCES.

TABLE II
SUMMARY VARIANCE TABLES
Comparison of Experimental Groups A & B
at 1 1/2 and 18 cps to Determine Whether the Groups are Different

Source of Variation	Degrees of Freedom	Sum of Squares	Mean of Squares	F Variance Ratio	Significance
Groups (G)	1	1.9	1.9	19.0	.001
Frequencies (F)	1	10.0	10.0	100.0	.001
Levels (L)	3	10.4	3.4	34.0	.001
GF Interaction	1	.6	.6	6.0	.001
GL Interaction	3	1.1	.4	4.0	.05
FL Interaction	3	0.0	.0	- -	- -
GFL Interaction	3	0.0	.0	- -	- -
Within cells	98	9.7	.10	- -	- -
Total	113	33.7			

Group A Analysis of Variance

Source of Variation	Degrees of Freedom	Sum of Squares	Mean of Squares	F Variance Ratio	Significance
Subjects (S)	5.0	2.56	.51	56.8	.001
Frequencies (F)	7.0	3.77	.53	58.9	.001
Levels (L)	3.0	10.15	3.38	375.6	.001
SF Interaction	35.0	1.14	.03	3.3	.01
SL Interaction	15.0	1.28	.09	10.0	.001
FL Interaction	21.0	.30	.01	1.1	- -
SFL Interaction	105.0	.94	.009		
Total	191.0	20.13			

Group B Analysis of Variance

Source of Variation	Degrees of Freedom	Sum of Squares	Mean of Squares	F Variance Ratio	Significance
Subjects (S)	8	8.89	1.11	35.7	.001
Frequencies (F)	8	20.46	2.56	85.3	.001
Levels (L)	3	33.91	11.30	37.7	.001
SF Interaction	64	10.75	.17	5.7	.001
SL Interaction	24	3.50	.15	5.0	.001
FL Interaction	24	1.01	.04	1.3	- -
SFL Interaction	165	4.44	.03		
Total	296	82.96			

FREQUENCY

	1		1 1/2		2		3		4	5		6	8	10	12	14	16	18	20	23	27
NOSE ITCHED AND TICKLED																		2		1	1
HEARING - POSSIBLY AFFECTED																1	1	1		1	1
SCALP TINGLED, AS DURING MASSAGE																1		3	1	1	1
NECK														1		1		3	1	1	1
EYEBROW AND EYELID FLUTTER													1	1			2		3	1	5
FACE MOVED OR TINGLED														2	1		1	3	6		5
THROAT - "LUMP" OR IMPAIRED SWALLOWING									1				1	1	1	1	2	4	1	2	4
TEETH "CHATTERED"								1		1				2		4		5		5	3
VISUAL (BLURRING, FIXATION, FOCUSING)	1		1		1	1	1		2	1	2	4	4	3	2	4	6	11	5	6	8
FACIAL (INVOLUNTARY-CHEEK FLUTTER, ETC)		1	3	1		1	1	1	1	1	3	1	2	5	6	7	2	15	7	5	3
HEAD	1	1	5	3	1	1	2	2	1		4	2	6	3	7	4	5	15	5	3	5
SHOULDERS	1	2	2	7	1	4	3	4	9	1	7	2	3	3	3			3	1		2
CHEST	1	4	3	11	1	3	1	3	5	4	4	5	3	5	5	2	1	1	2		1
SPEECH DISTORTED OR FORCED	1	1	3	3	1	3	2	1	1	2	1	1	1	1	2	1					
BREATHING DIFFICULT														1							
TRUNK	1	1	3	4	1	3	2	2	1	3	2	1		2		1		1		1	
ABDOMINAL CAVITY		3	4	7	2	6	2	2	4	2	5	4	4	3	1	1					
VALSALVA MANEUVER	1	1	2	2	1	1	1	1	1	1	2	1	2	1	1		1				
BUTTOCKS	2	1	4	1	2			1					1								
PELVIC			1	1						2	1		1								
CALVES												2	1			2	1	1		1	
THIGHS								3			2	2	2	1		1					
KNEES			1	1		1		2	2		1	1		2		1		1		1	
LEGS			3	2		1	3	2	1		3	5	4	2	1					1	
ARMS	2	2	5	5		3	2	3	5		2	1	3	4	1						
FEET	1		5	1	1	1			1		1	4	4	1	1		1			1	
WHOLE BODY AFFECTED	1	3	3	3	2	1	2	1	3	2	3	3	4	4	2	1	2	1		1	1
MOVEMENT RESTRICTED	4		6	1	3	1	1	1	3	3	1	2	2	3	1	3	1	5	1	3	1
FIGHTING MOVEMENT	2		2	1	3	1						1									
MUSCLES TENSE	2		1	1					1			1									
LOOSE FLESH "JARRED"	1		1		1																
FEELING OF RELAXATION									1	1		1		1		1		1		1	
CONCENTRATION AFFECTED			1	1			1	1		1			1	1	1	1	1	2		2	
SLIGHT DIZZINESS														1							
MOTION SICKNESS TENDENCIES/ DISORIENTATION	5		4		4								3		2	1	1			2	
VISUAL ILLUSIONS	1		2		3	2												3	1	1	1
FATIGUE	2		3		4				1							1					
BECAME IRRITABLE														1	1						
SUMMARY: HEAD	2	2	9	4	2	3	4	4	5	3	9	7	14	19	17	23	20	34	[illegible]	29	37
SUMMARY: THORACIC ABDOMINAL	7	12	22	36	9	20	11	14	21	15	22	14	17	16	12	5	2	5	3	1	3
SUMMARY: EXTREMITIES	3	2	14	10	1	6	5	16	9		9	15	15	10	3	4	2	2	2		4
SUMMARY: GENERAL	10	3	14	6	9	3	3	2	7	5	4	7	6	7	3	4	3	6	1	4	2
SUMMARY: PSYCHOLOGICAL	8		10	1	11	2	1	1	2	2	1	1	4	4	4	4	2	6	1	6	1

TABLE: 3 A SUMMARY OF BODY AREAS AFFECTED OR BODY FUNCTIONS DISTURBED. (ENTERED AS BODY AREA AFFECTED VS. THE FREQUENCY AT WHICH THE EFFECT WAS NOTED BY THE SUBJECT OR EXPERIMENTER. ENTRIES IN THIS TABLE INDICATE THE NUMBER OF REPORTS. THE DIVISION INTO TWO GROUPS FOR FREQUENCIES 1, 1½, 2, 3, & 5 REFLECTS REPORTS ON TWO RUNS, ONE AT THE BEGINNING OF THE EXPERIMENT, THE SECOND AT THE END. CONDITIONS WITH FIVE OR MORE REPORTS ARE CIRCLED TO EMPHASIZE TRENDS).

DISCUSSION

As the first experiment in a series designed to study effects of vibration on human performance, this research was designed to permit selection of vibration intensities for performance testing and to provide a general orientation for later experiments. Other studies (e.g. References A, F, P) have shown that vibration accelerations humans will accept varies according to frequency. Assuming that these (varying) acceptable accelerations are indicators of body limits for vibration accelerations, it followed that arbitrarily defining constant accelerations or amplitudes for the different frequencies could involve undesirable potential danger, such as exceeding physiological limits that were not included in the purpose of this program. Since accepted acceleration range had varied with frequency for other studies, it also followed conversely that performance measures should be made over a broader acceleration range at some particular frequencies than at others. This approach would be necessary to insure inclusion of performance data over the vibration ranges which are acceptable to human subjects, and therefore, might occur in operational manned systems.

Disagreement between referenced reports in describing acceptable vibration ranges led to the conclusion that these differences might best be resolved by independently deriving appropriate vibration levels for the performance tests of this program. Accordingly, subjects identified a series of vibration intensities as being (1) definitely perceptible, (2) mildly annoying, (3) extremely annoying, and (4) alarming, in this experiment. The four vibration levels so defined would then identify vibration conditions at which later experimental measures of performance could be made.

Analysis of the data indicated that integration of individual datum points into a summary curve was feasible, although certain restrictions must be recognized. These restrictions are:

> Significant differences between subjects were indicated, evidently because of a difference in orientation and framework. This indication was shown by differences between successive test groups, i.e., Group A followed by Group B with Group B defining significantly higher accelerations for the four judgment levels. No correlations to aid in explaining this relation could be found between judgment level and body type, experience, or procedures. Reanalyzing differences in test conditions indicated the following potentially significant influences: Medical monitor (a different M.D. was assigned to each group), subjects, and calendar sequence (Group A having completed the tests before Group B started). Medical procedures were unchanged

(thus minimizing possible influence from M.D. change) and there was no obvious difference between subject groups which could lead to the reported differences. The major distinction between groups was in Group B's knowledge that the entire procedure had been completed without problems. Evidence of a similar factor contributing to differences between subjects within each group was found in the comment of one Group A subject who accepted higher accelerations. He felt that with the control he had of the system and other precautions taken for the subject's welfare, there was really nothing to worry about. Conversely, (and illustrating the varying frameworks) another subject rejected the scale to be used and substituted a personal, more conservative definition for the four levels.

Since vibration curve trends were similar for all subjects, the differences are considered to be related to semantics (or the meaning of words as influenced by personal background knowledge). Therefore, the derived levels could be accepted as usable for their intended purpose as the vibration level intensity for succeeding experiments.

The variation in acceptable acceleration ranges according to frequency found by previous human vibration researchers was supported by the data. Not only were acceleration differences between levels found, but accelerations were relatively higher in the 1 1/2 and 18 cps ranges. The data differed particularly from prior research reported in that an increase in acceleration paralleled increasing frequency from 8 or 10 to 18 cps. Although Zeigenruecker and Magid (Reference P) report a parallel function, Gorrill and Snyder, and Goldman (References A and F) report nearly constant accelerations in these frequency ranges.

Analysis of the latter two studies indicated that differences in equipment and subject configuration which appeared to contribute to differences in data which are noted in the curves of figure 6. Gorrill and Snyder used an aircrew seat of different configuration, an ejection cushion, full flight gear (helmet, coveralls, boots, parachute, and oxygen mask) lap belt, and shoulder harness. The different judgment levels required subjects to project their responses over time, e.g.: This vibration actually experienced for 2.75 minutes in the laboratory could be endured for one hour, 15 minutes, or two to three minutes in a hypothetical operational mission. Chair configuration, foot rests, and control wheel differences appear to present the greatest potential source of differences in experimental results. A strong cushioning effect would be associated with the vibration at the seat, raising questions about comparability of this vibration to the present study even though measured accelerations might be the same. The cantilever arrangement of the foot rests used in that study may have permitted strong resonant accelerations on the sole of the foot prior to any other part of the body. The control column arrangement would have permitted similar inputs to the palms and instructions would have permitted any of these inputs to be recorded.

There were not so many differences in configuration between the current study and reports included in Goldman's data. Checking his references revealed that emphasis was on comfort as a passenger in wheeled vehicles, which would provide a different orientation of subjects. The use of seats from automobiles in a vibration exciter suggests an effect from cushioning as potentially influencing results in the data summary reported by Goldman. Parallels in results from the present experiment with the curves and test configuration reported by Zeigenruecker and Magid (Reference P) are more evident. In their study, foot rests were firm, reinforced board seats with no cushions used and the seat configuration appeared similar to those of the present study. Subjects differed from the present study in that a helmet, extended hand grasps attached to armrests, and shoulder straps were used. Test configurations and supports, and subjects operational framework appear to be related to discrepancies between studies.

The curves obtained by integrating the data and plotting a smooth function were plotted on a special coordinate system for analysis of vibration judgments vs velocity, acceleration, and double amplitude. The curves of figure 4 indicate that velocity was essentially constant for judgments at 1 and 1 1/2 cps. Above 1 1/2 cps, acceleration was relatively constant, but associated frequency range varied according to judgment level for 2 to 6 cps. Acceleration was constant for level 1; 2 to 8 or 10 cps for levels 2, 3, and 4. Then emphasis shifted primarily to a function of double amplitude up to 16 and 18 cps, although level 4 approximates constant velocity in this region. Above 16 and 18 cps, judgment levels are best described as being a function of double amplitude vs acceleration. Accelerations were higher near the frequencies of 1 1/2 and 18 cps, lower at 1, 4 to 10, and above 20 cps.

Reference to individual curves in the appendix and in figures 6 through 14 indicates that overlap between levels among the subjects judgments occurred but suggests that distinct differences between levels do exist. This is further supported by the results of statistical analysis shown in Table II with less than one chance in 1,000 that the obtained distinctions in levels are out of the ordinary. Study of these figures also suggest that judgment or acceptability of vibration is affected by frequency, (supported by statistically significant frequency-judgment level interactions) and that subject differences are significant. Figures 7, 9, 10, 11, 12, and 13, effectively present the latter comparisons, with maximum accelerations for a given level varying (for different subjects) from 1 to 4 and 16 to 20 cps. However, the general curve trends are similar for all subjects.

Analysis of interview data and body characteristics were conducted to determine whether any statements or characteristics could be correlated with responses obtained, with changes in frequency, or with changes in acceleration.

Some of the effects from changes in frequency or acceleration are discussed with the curves. The major added factor from the interview analysis was the definite correlation between affected body area and frequency indicated in Table I. Two trends are shown by tabulation of reports of affected body area vs frequency. The effect shifted from the buttocks and lower thoracic abdominal areas at low frequencies to the upper body areas as frequency increased, and were concentrated in the head region at 27 cps. The reports of effects on extremities were less clear cut, but a similar trend occurred. Here, the trend was from whole extremity effects to localized areas as frequency increased. These shifts in affected area vs frequency show considerable overlap of effects in the vicinity of 8 cps, with a large total number of reports in this region. The literature (e.g. References A, E, F, L) suggests general acceptance of a theory of internal organ resonance and Magid and Coermann (Reference L) report supporting evidence for this concept. However, it is possible that an added factor which has contributed to lowered threshold is a psychological summation of effects from the many body regions responding to vibration at these frequencies.

Table III correlations of frequency and body effects, combined with the curve analysis at specific frequencies described earlier, were expected to provide information for analyzing differences in judgment of vibration related to body characteristics. However, no specific correlations were obvious. Although the analysis was somewhat gross, it is suspected that distinct definition of body characteristics using subjects who are clearly representative of each body type category, and with more sessions per subject, will be necessary to clarify any relation between body type and psycho-physiological response to vibration. A more accurate method of body typing may also be required.

Similar study is considered necessary to adequately analyze variation in diet, elimination, and rest. Relatively minor control of these items was sufficient to insure that subjects habits were similar, so that no discrepancies from living habits could be expected, nor were any discovered.

Data Application Possibilities

In considering application of the data reported, certain restrictions must be considered. The vibration levels derived in this study are for short time periods with sinusoidal vibration only, and are apt to decrease with longer exposure times since vibration is considered to have an accumulative effect. Magid and Coermann (figure 6) presented data showing the decrease in tolerance limits as exposure time increased. It will be noted that data curves from increasing exposure time to three minutes for that study overlap the curves for this study. For this reason it is considered highly desirable to avoid the fourth level accelerations in this region (3 to 8 cps).

Combining this information with known aircraft vibration acceleration peaks, it is known that aircraft peak accelerations exceed the levels from this study on an occasional basis although the effects on operator performance are not clear. From this, it is concluded at this time that occasional exceedance is acceptable, but that long or repetitive sequences exceeding these levels are highly undesirable in terms of bodily effects. Knowledge of effects of these accelerations on performance are not known - more conservative planning for operational vibration spectra may become necessary as remaining studies in this project are completed.

For the design engineer, the most useful application of these curves would be in making decisions regarding amount of vibration to be permitted in the crew environment and modifying vibration by structural or other methods to dissipate the energy at a frequency less troublesome to crew members.

Insight into the effects of vibration on specific parts of crew task requirements as part of the job function may also be obtained. Reviewing Table III in conjunction with the task "parts", will permit understanding the most likely task parts and most critically affected performance requirements. (With this information appropriate provision in design planning should be of assistance in defining better task requirements and probable vibration effects on associated performance.) Directly applicable information on the amount of these effects will become available as part and combined tasks are studied for effects of vibration on performance later in this program.

Future Study Requirements

Some studies that could be considered desirable or necessary have already been suggested. During the preparation and conduct of experimental efforts to date, a need became obvious for information in several areas not directly related to this program but pertinent to understanding, integrating, and applying results of this and other programs.

One of the more pressing requirements is for a complete literature review and integration of human vibration reports which are readily available for distribution. Bibliographies and reviews which are available tend to be oriented toward a particular application or interest area and are limited in scope accordingly. A good general bibliography, review, and integration of all data from all reports into a human vibration design handbook is required. The nature of the available reports and of the disciplines that have been interested in the field suggest that a comprehensive review would best serve its purpose if divided into three major sections: (A) Human Engineering Design Data, (B) Psychological Data, and (C) Physiological Data.

Very little research on effects of random vibration from operational vibration environments has been reported, most studies having been concerned with defining effects from sinusoidal vibration. While these efforts have been useful in clarifying relationships, they do not fully define the problem. No data are available for defining the extent to which sinusoidally derived data can be applied in the random vibration environment, although some exploration has started and are reported in D3-3512-2 of the current series. These data, preferably in the form of conversion factors (or a transfer function) are necessary to predict effects of a given operational vibration environment on performance. Failure or inability to discover such functions may require human operational testing for each new vibrating system to fully determine vibration effects on capability. It also may mean that data derived with sinusoidal vibration is of little value for operational application. For similar reasons, the effects of long time exposure to sinosoidal and random vibration require study.

In the rationale for the scaling (or levels) system used, it was suggested that semantic differences could be reduced, and more consistency between subjects result, if other techniques for psychological scaling were used. As indicated, these techniques were not used in this experiment because the processes involved were too complex and time consuming for completion within the scope of this program. Review of the data and the support given (which indicates that semantic, or word meaning, differences between subjects were present) indicate that extensive study to define vibration descriptions more precisely is desirable. This study will be necessary if the most precise description of psychological response to vibration is desired, or if a more consistent psychological description of vibration is to be derived.

A combination of precise psychological scaling and knowledge of the mechanics of individual and combined body organ and tissue response is considered necessary to fully define body resonance and sensitivity to vibration. Any attempts to correlate body type and other features with psychological and physiological response to vibration will be gross (and resultant discrepancies between studies are expected to continue) until this information on scaling and mechanics is made more precise.

Knowledge of body organ response and the psychological effects are particularly desirable for study to adequately identify restraint and support systems for vibrating environments. The directional axes and extent of vibration relative to restraint, supports, and seating arrangement may require extensive data and analysis to arrive at an optimum configuration for a given condition.

Other areas that emerged as being pertinent to better describing vibration effects were based on literature reviews, analysis, and observation. In view of tradeoffs for training requirements, age, weight, and environmental support vs. payload (particularly for aerospece systems), exploration of these factors for correlation with vibration sensitivity appears desirable. The large difference between male and female humans in weight and certain performance capabilities should be investigated, particularly since Shaeffer et al, (Reference N) have demonstrated sex-age differentials for vibration acceptance in other animals.

APPENDIX A

EXPERIMENT ONE
INSTRUCTIONS TO SUBJECTS
EFFECTS OF VIBRATION ON HUMAN PERFORMANCE

Since outside discussion may change individual viewpoints and cause an undesirable competitive situation, you are not to discuss the instructions or definitions with anyone but the Human Factors Experimenter. We are interested in your best judgment only.

A. For this experiment, you are asked to think of vibration as a general situation, where no particular operations are required and no reference to a particular environment is desired.

B. You are to evaluate the changing vibration carefully and indicate each level of vibration defined by pressing a button which will be under your right index finger.

C. Under no condition are you expected to go beyond the 4th level. Immediately after you have pressed the button for this level, you are to release the switch under your left fingers to stop vibration.

D. It is necessary to evaluate very carefully to determine whether all levels really exist, since the machine has been limited.

E. If, in your opinion, vibration becomes too severe at <u>any</u> time, you are to stop the machine.

F. The study will stop at the 4th level, although others are defined to clarify the definitions.

The definitions are as follows:

1. Definitely perceptible.

2. Mildly annoying.

3. Extremely annoying.

4. Alarming.

You are to stop the machine here. The remaining definitions are to describe the rest of the range only.

5. Limit of physical control.

6. Limit of voluntary tolerance.

Another term, "Threshold of Perception," precedes "Definitely Perceptible." "Threshold of Perception" will not be defined as part of this test.

At the end of the second test for the day, the following instructions were given in preparation for the third test:

For this test, the procedure will be changed. You will identify the four levels as you have been, but will not stop the machine at the fourth level. Instead, the acceleration onset will be reversed as you press the button so that you can identify the first three levels in reverse order. The identification order will be 1, 2, 3, 4, 3, 2, 1.

APPENDIX B

This portion of the report illustrates the four levels of vibration (definitely perceptible, mildly annoying, extremely annoying, and alarming) defined by each individual subject. The captions used identify the subjects for reference to the curves of figures 6 through 14.

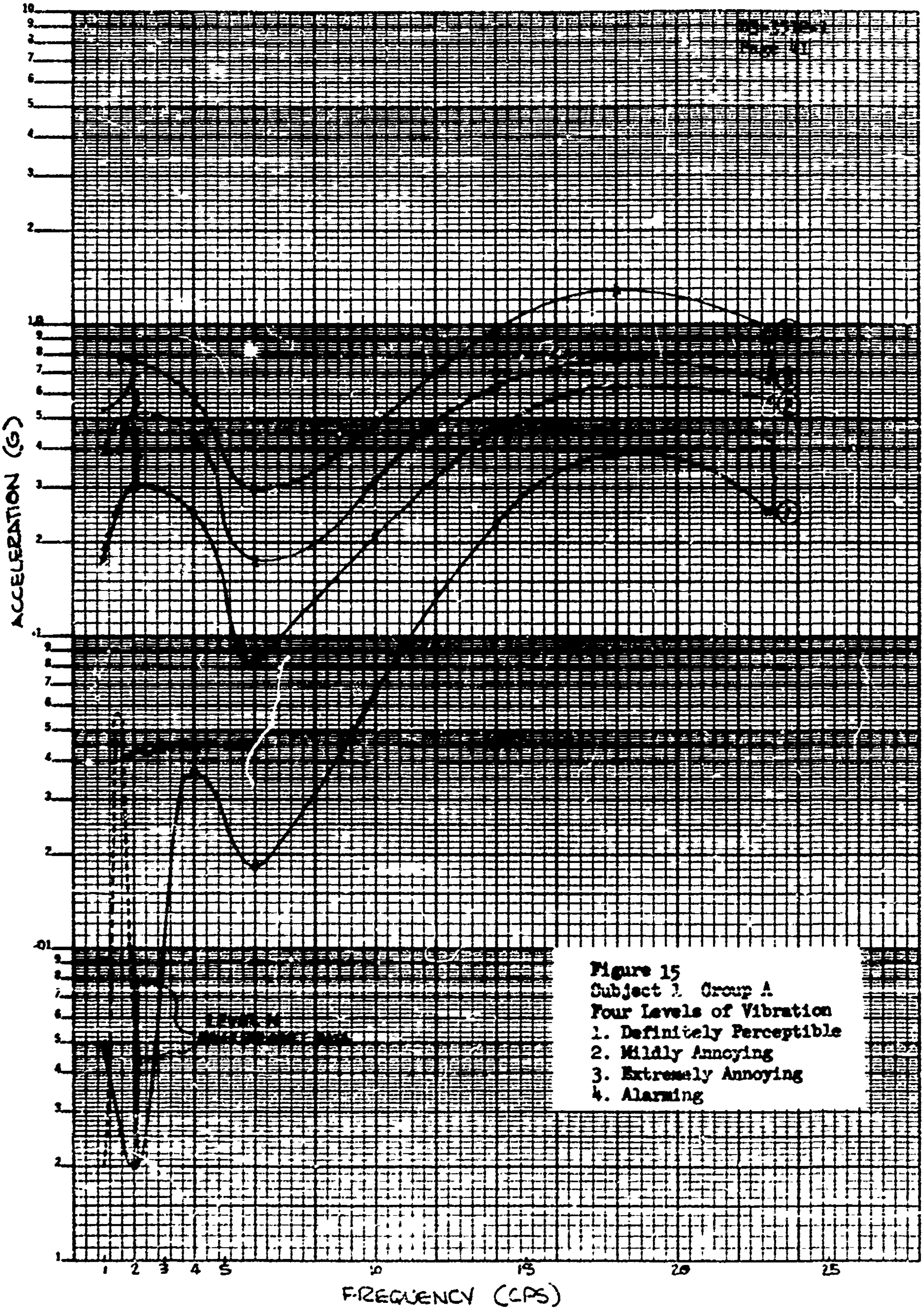


Figure 15
Subject 1 Group A
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

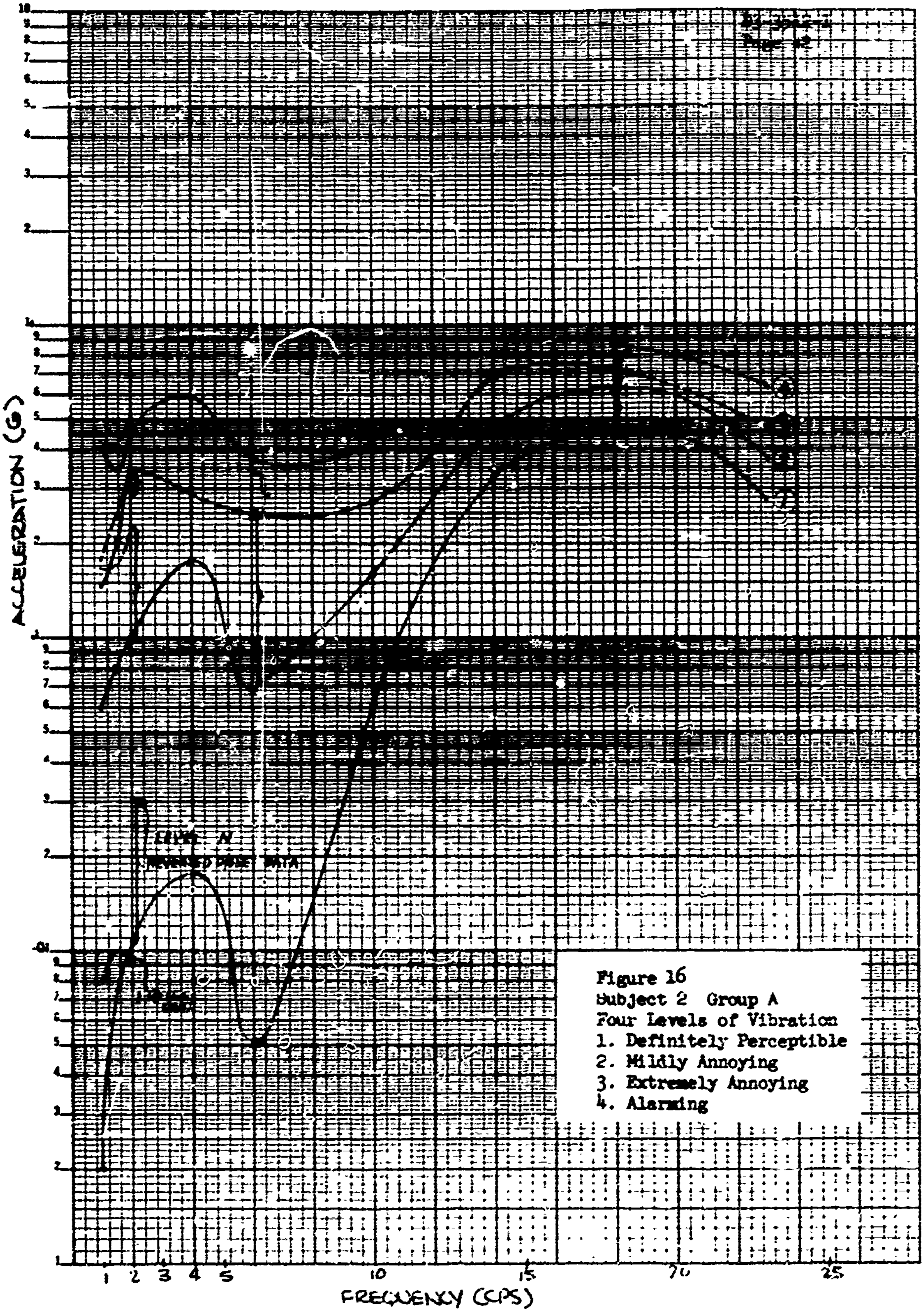


Figure 16
Subject 2 Group A
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

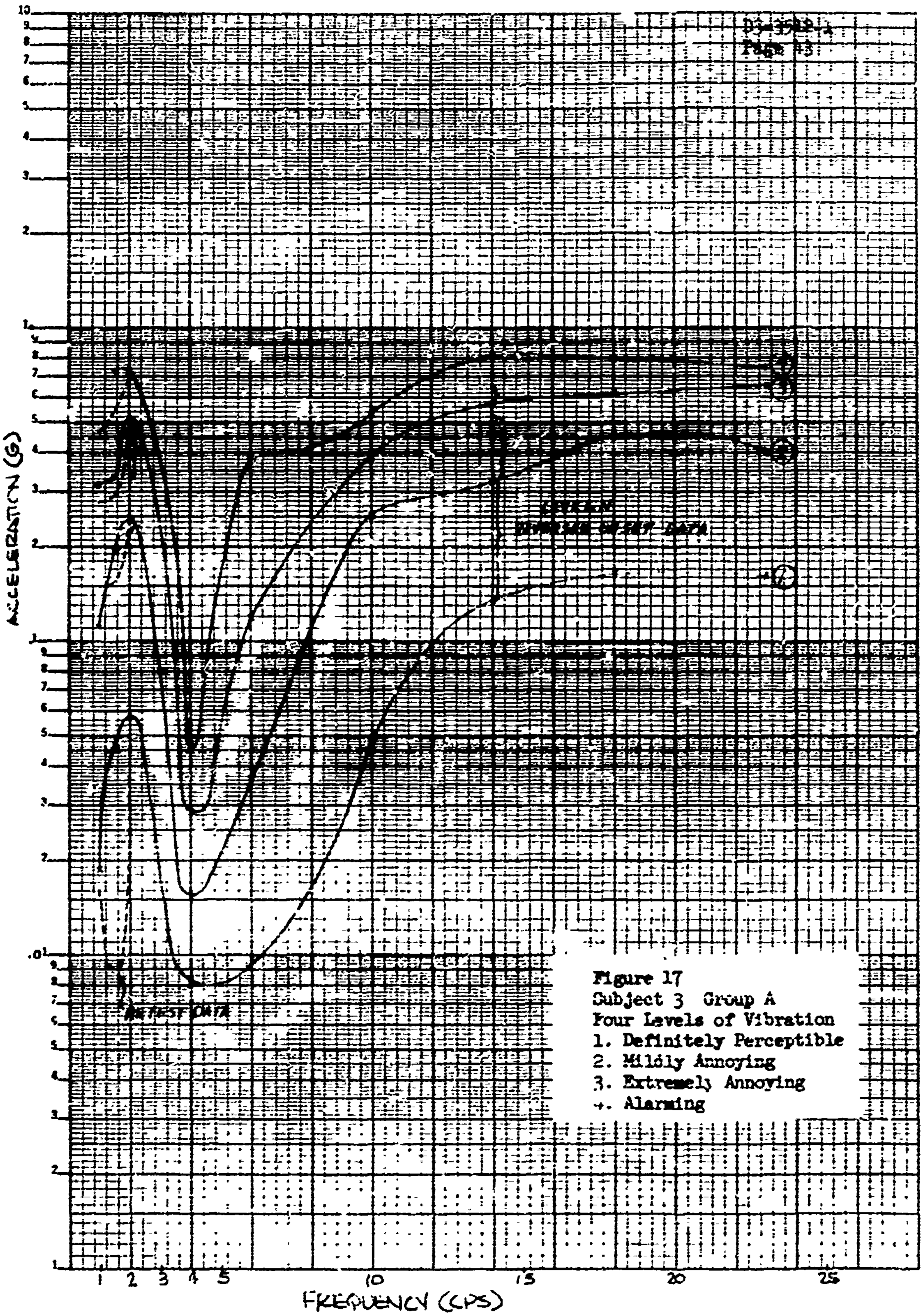


Figure 17
Subject 3 Group A
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

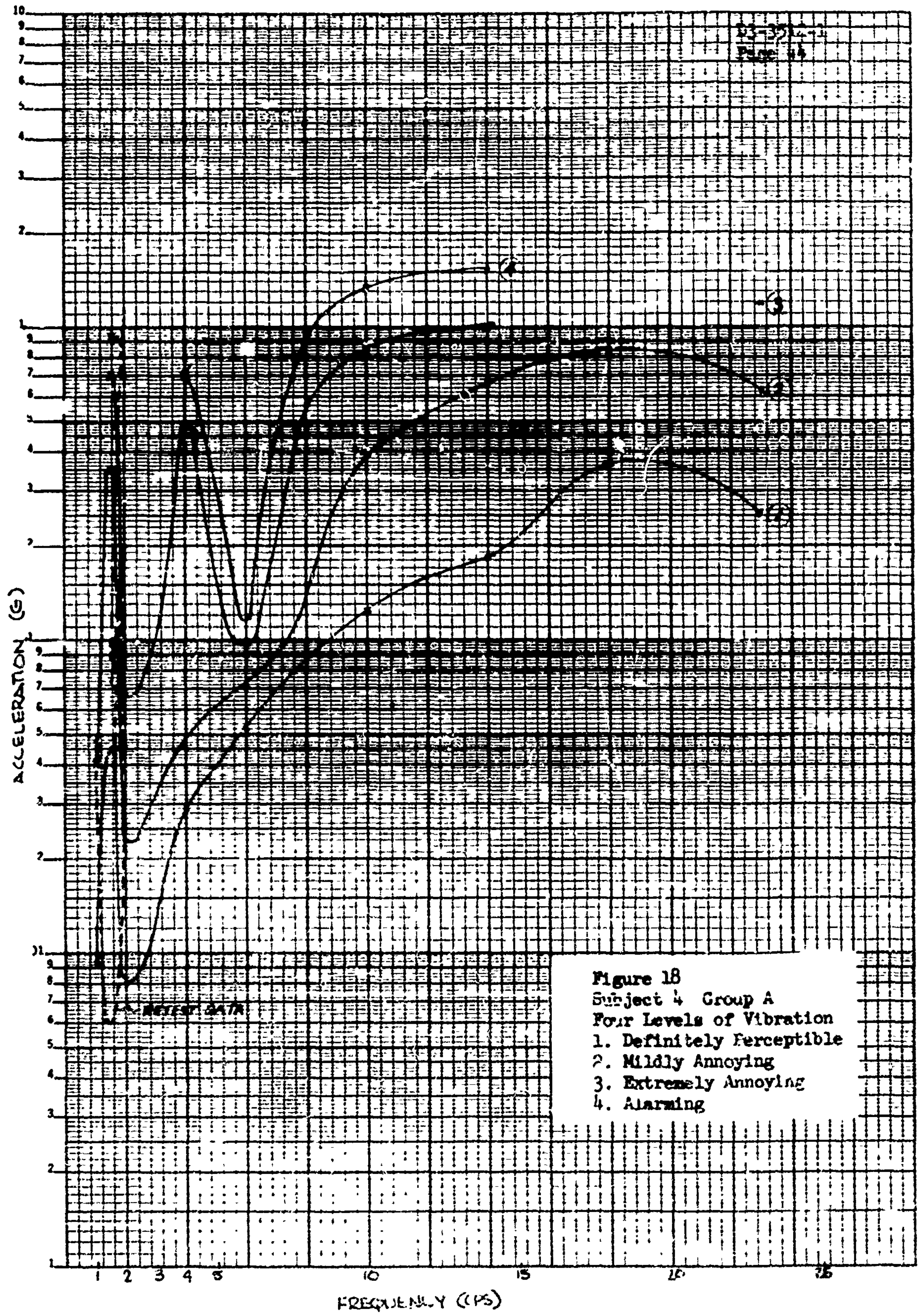


Figure 18
Subject 4 Group A
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

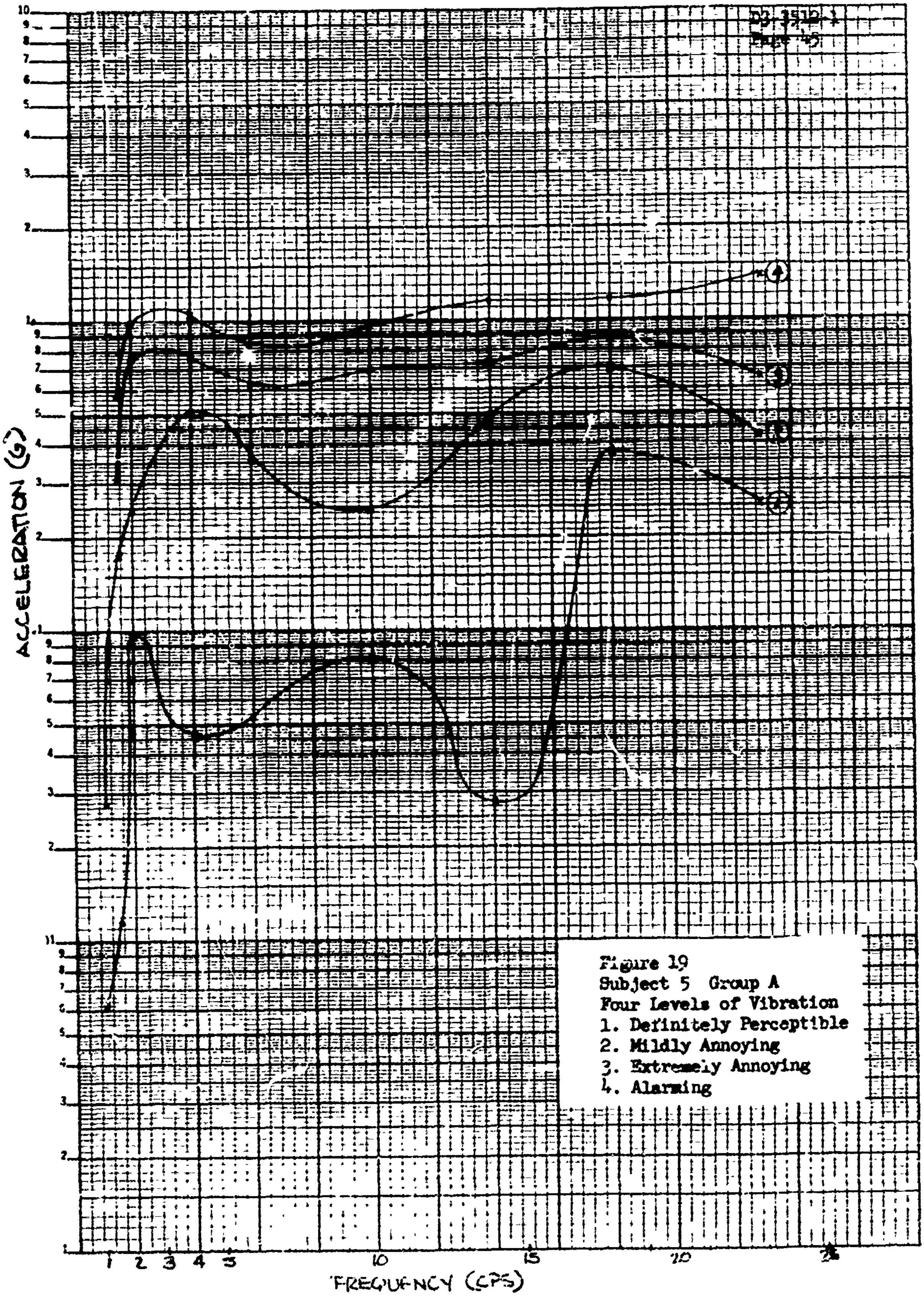


Figure 19
Subject 5 Group A
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

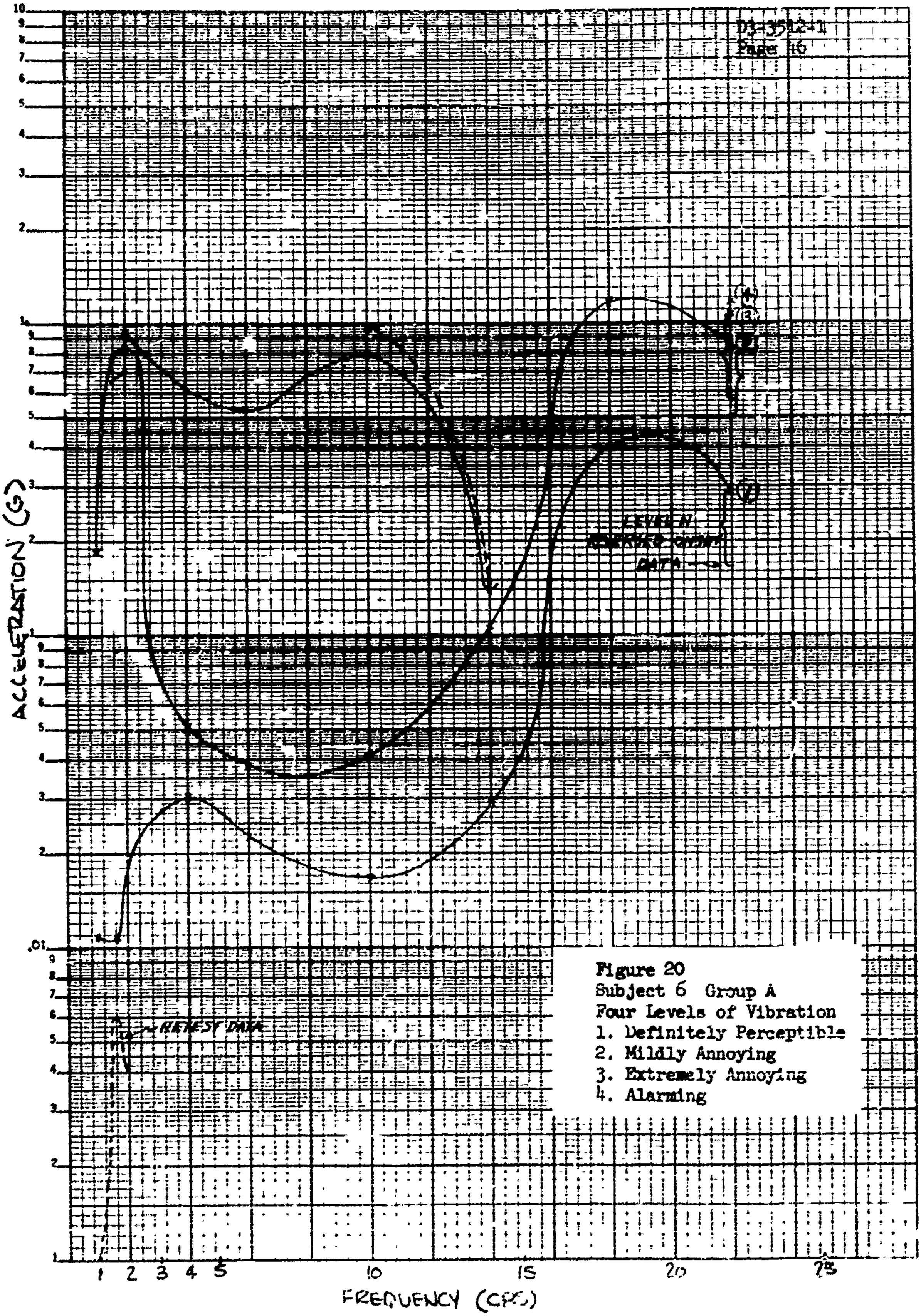


Figure 20
Subject 6 Group A
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

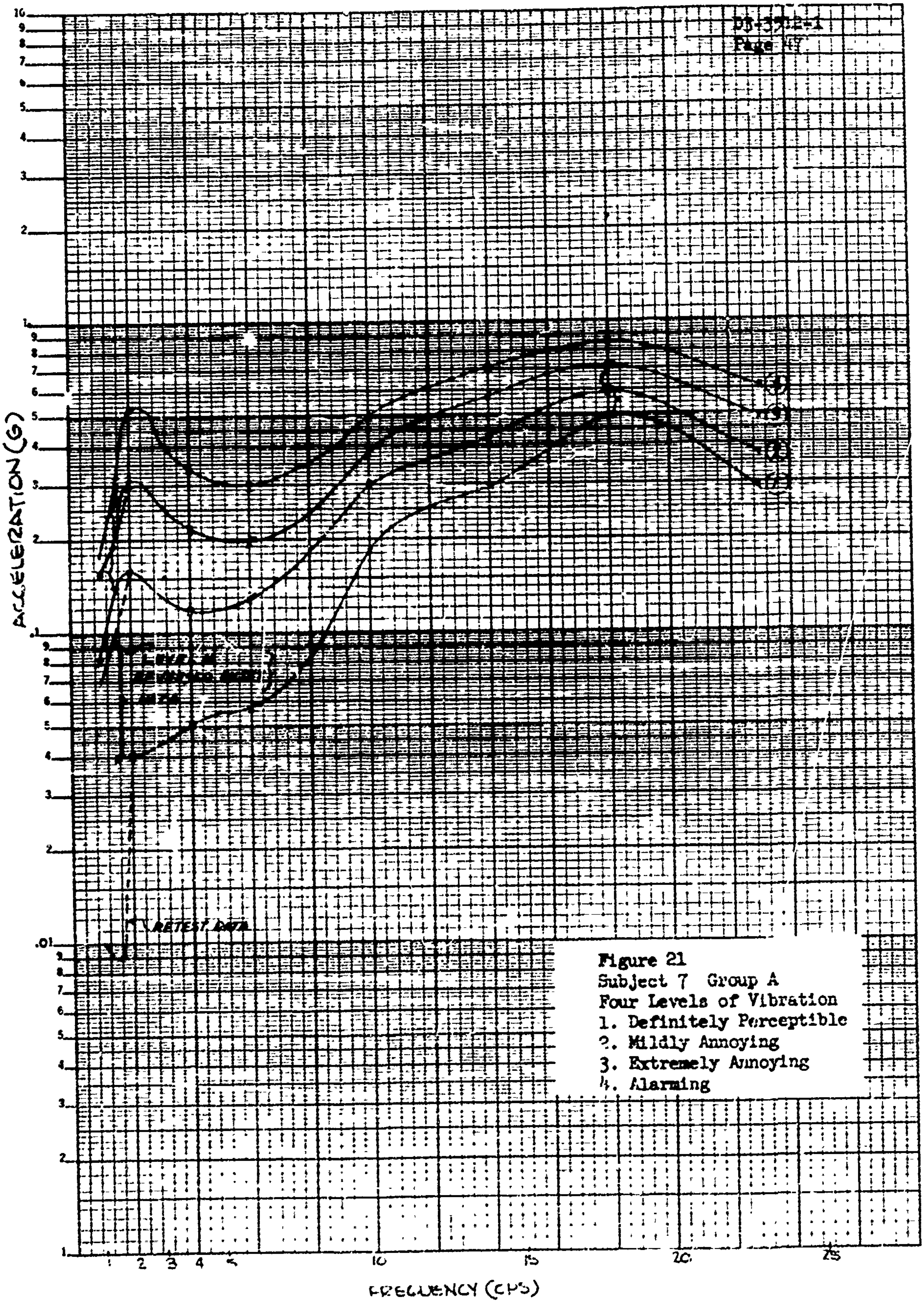


Figure 21
Subject 7 Group A
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

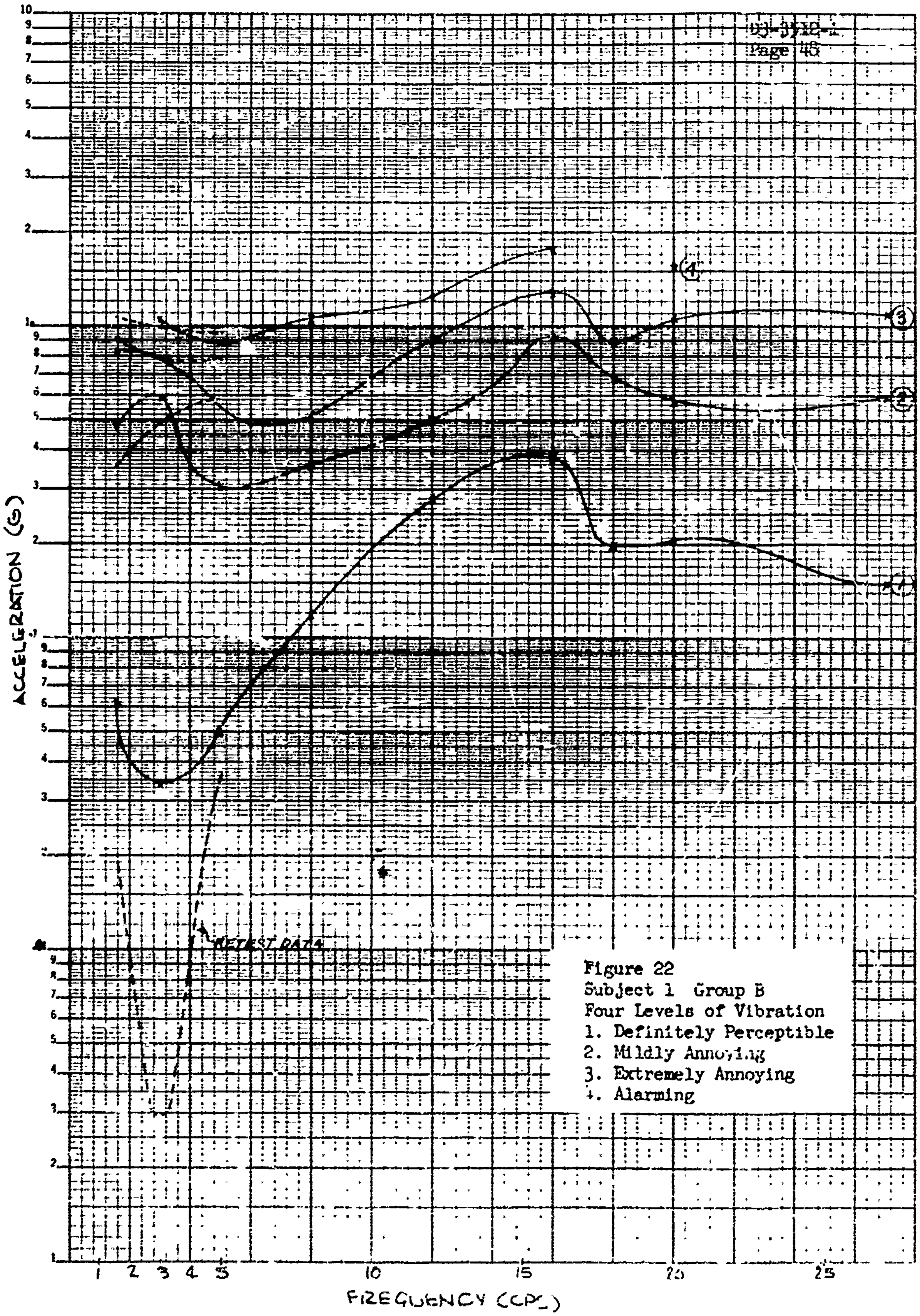


Figure 22
Subject 1 Group B
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

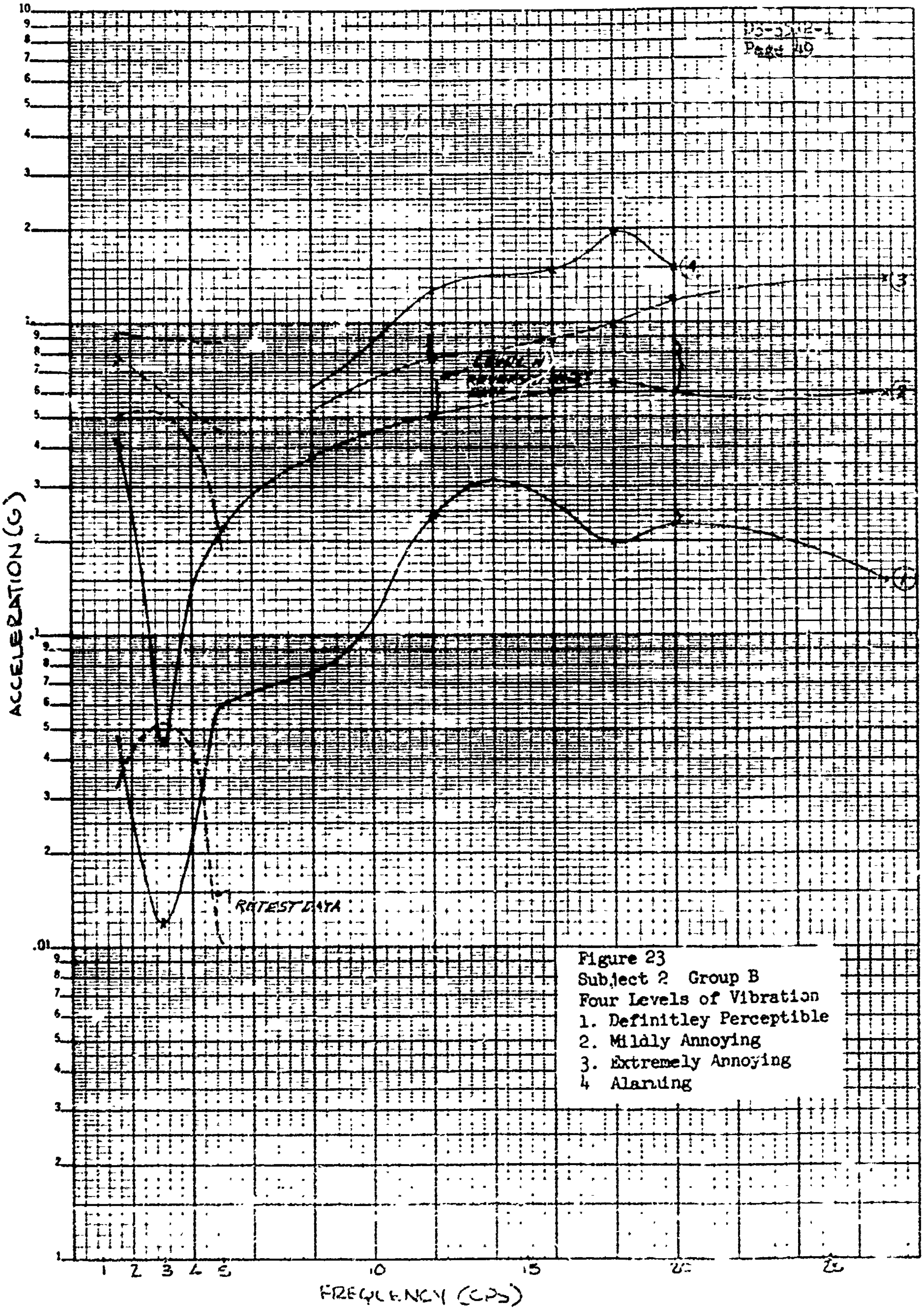


Figure 23
Subject 2 Group B
Four Levels of Vibration
1. Definitley Perceptible
2. Mildly Annoying
3. Extremely Annoying
4 Alarming

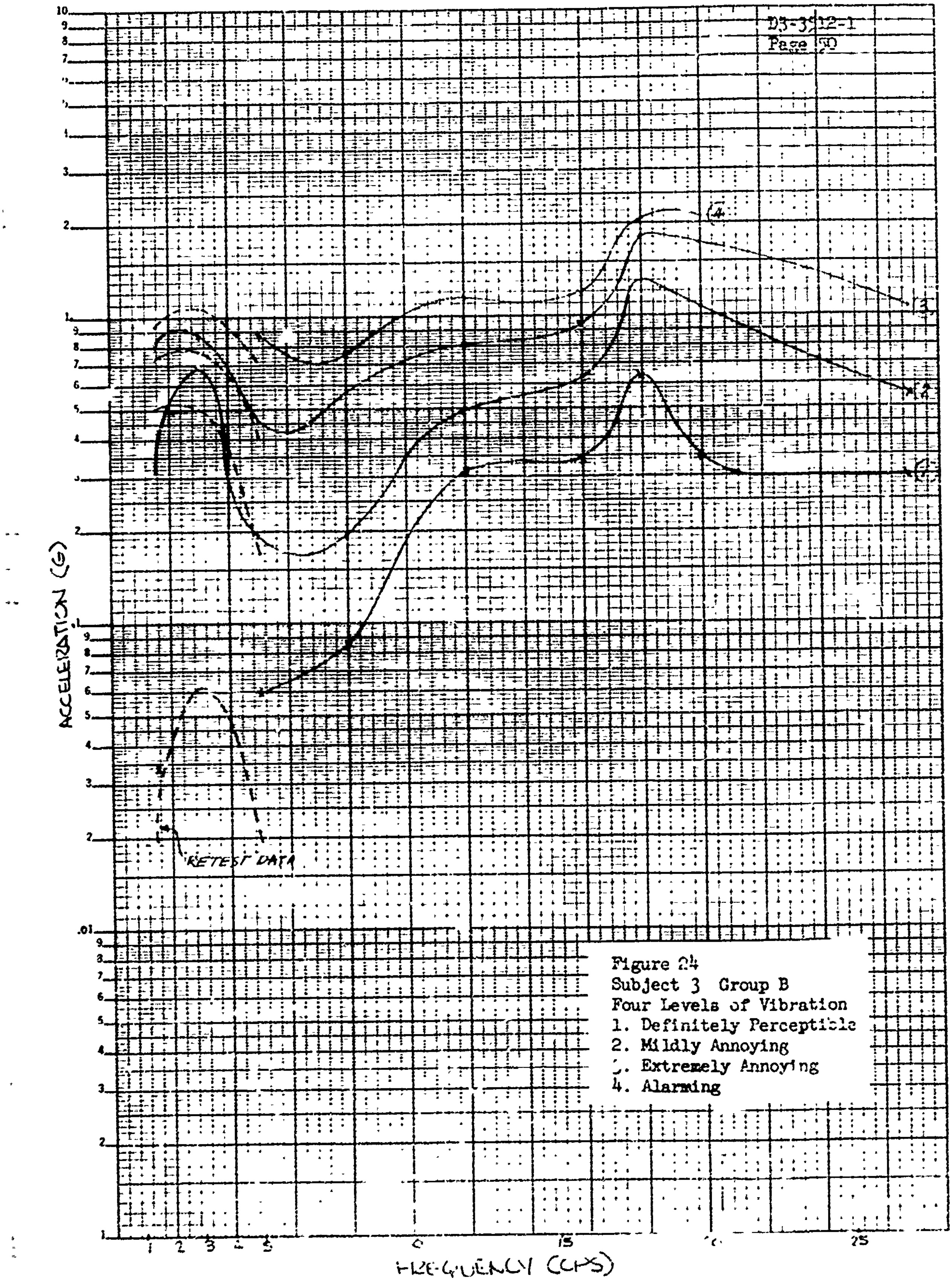


Figure 24
Subject 3 Group B
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

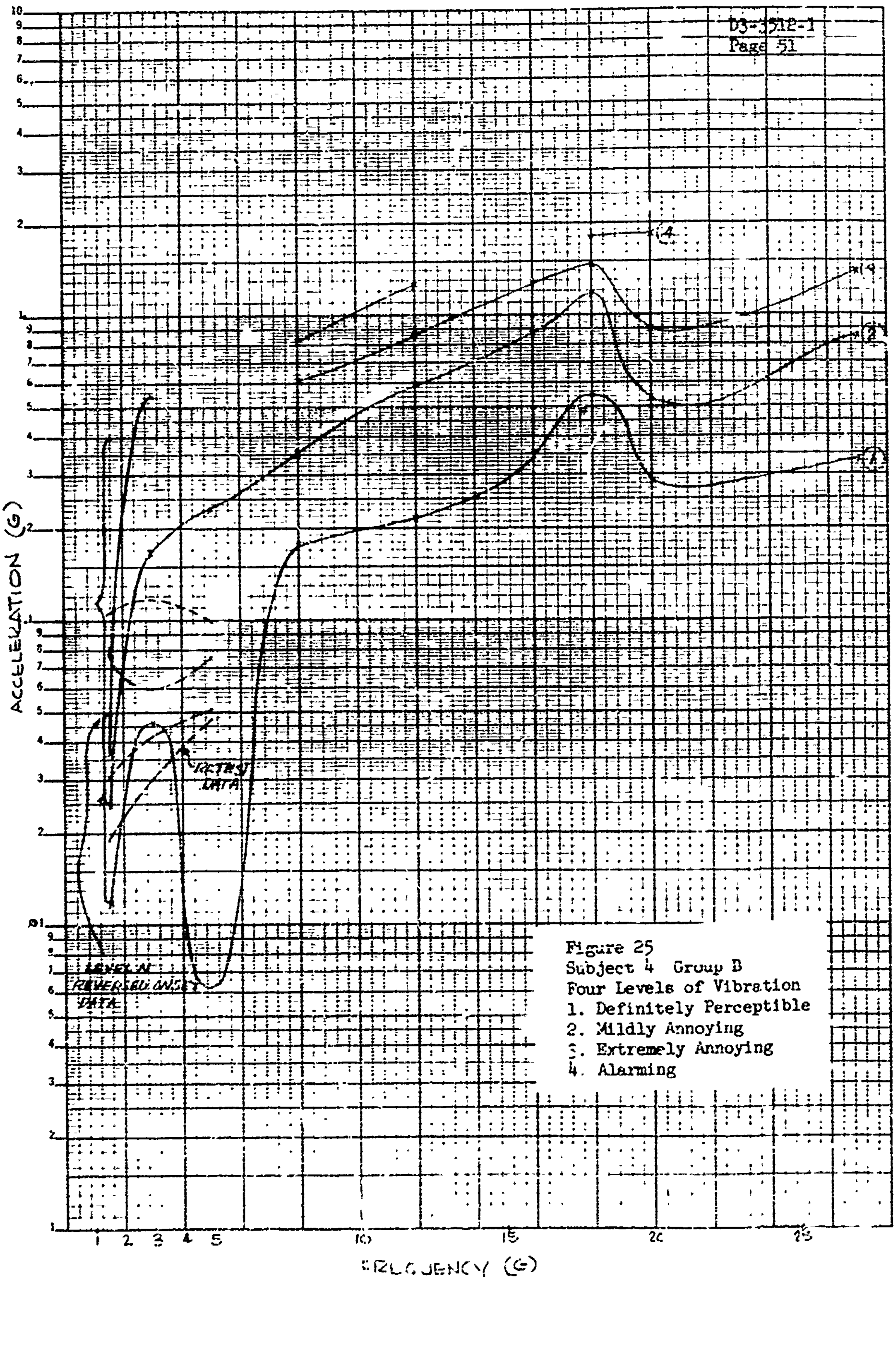


Figure 25
Subject 4 Group B
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

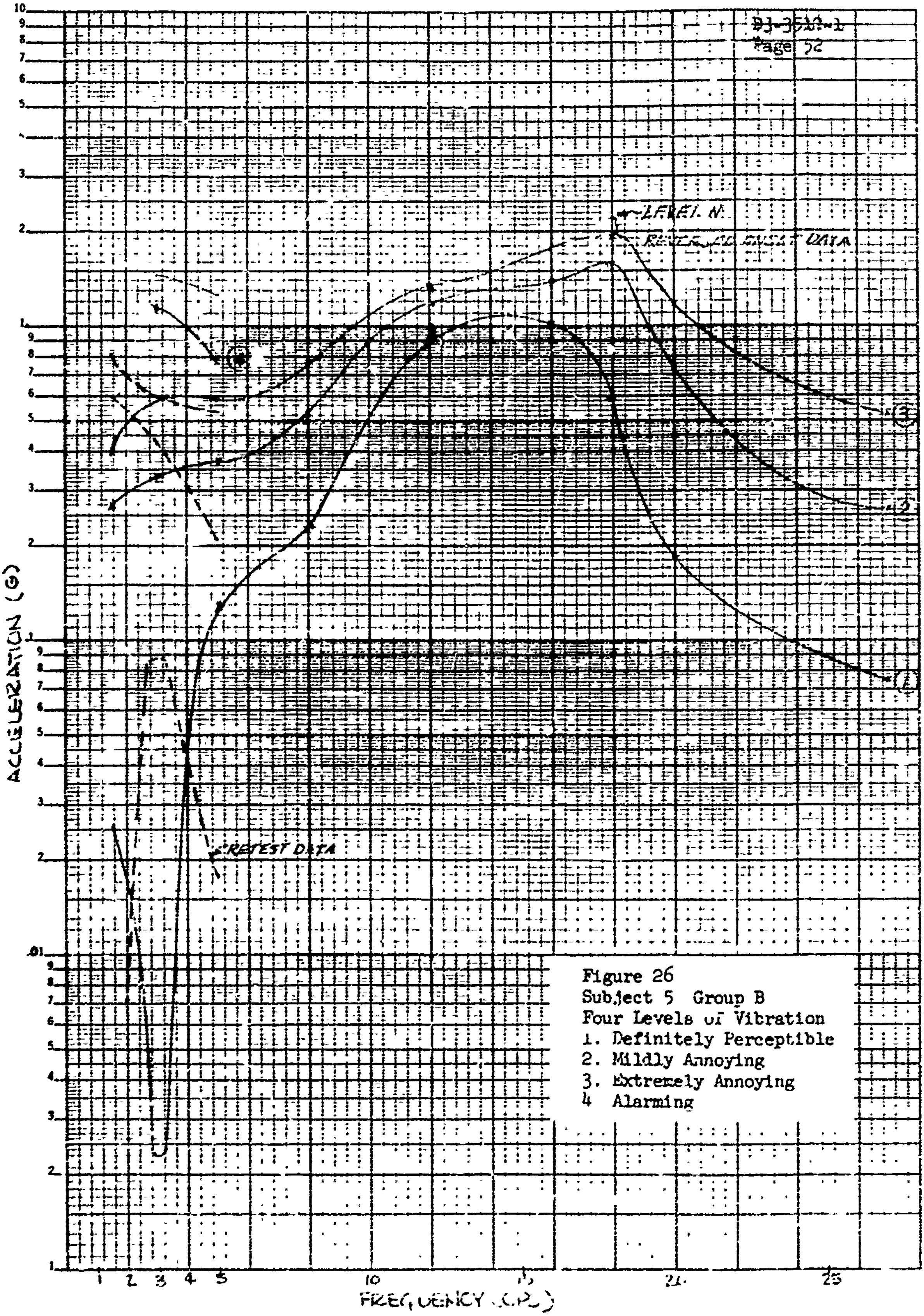


Figure 26
Subject 5 Group B
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4 Alarming

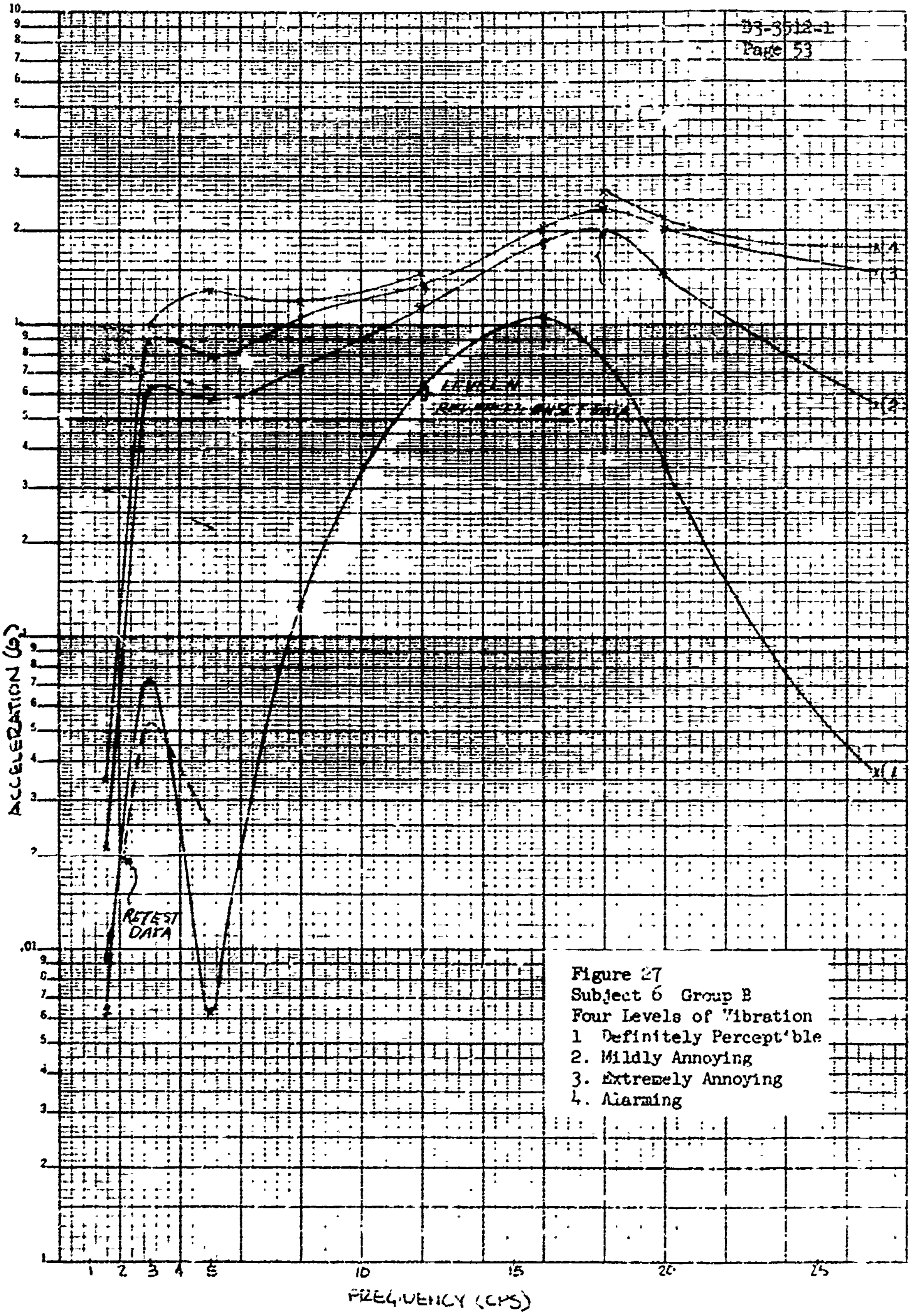


Figure 27
Subject 6 Group B
Four Levels of Vibration
1 Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

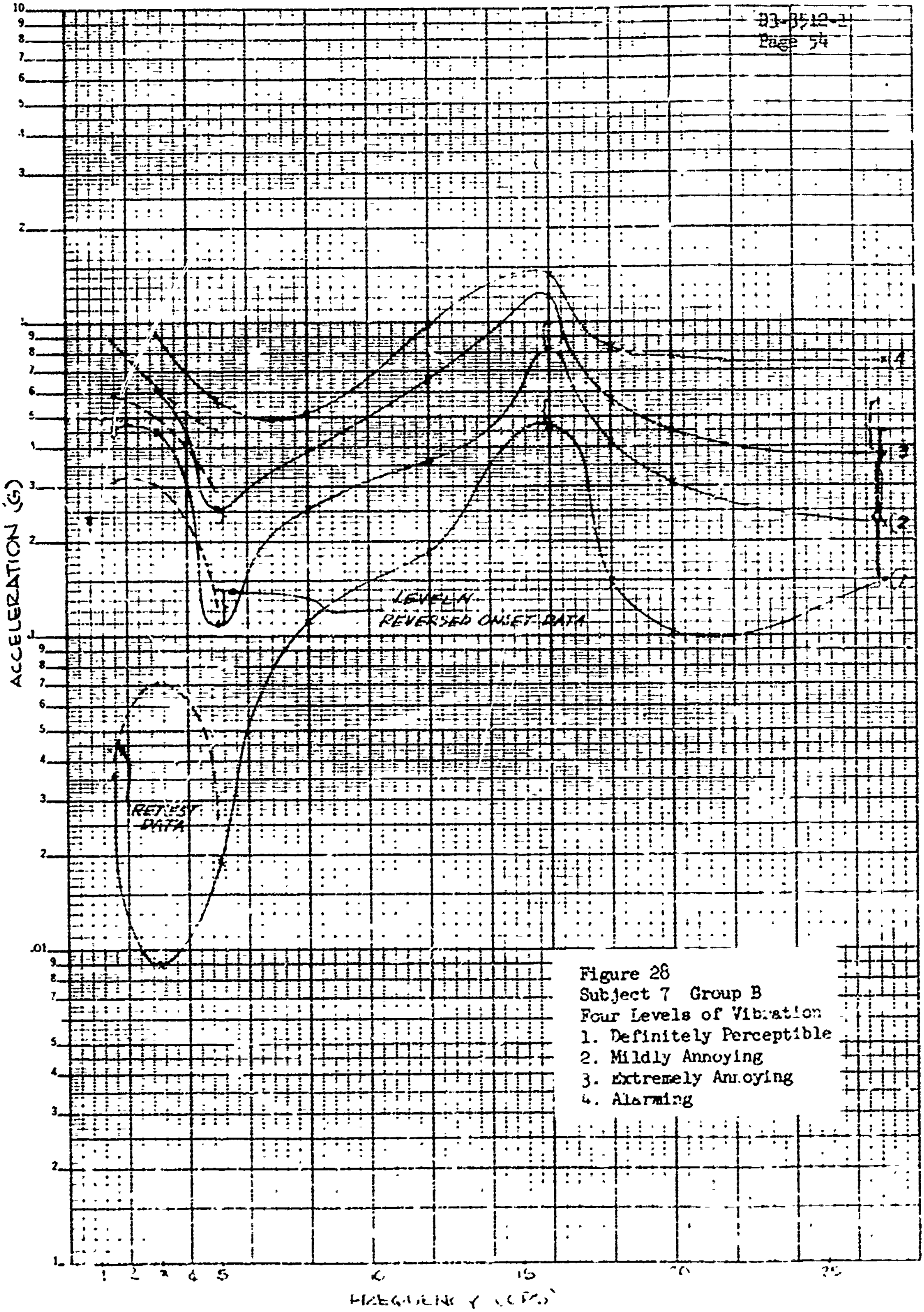


Figure 28
Subject 7 Group B
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

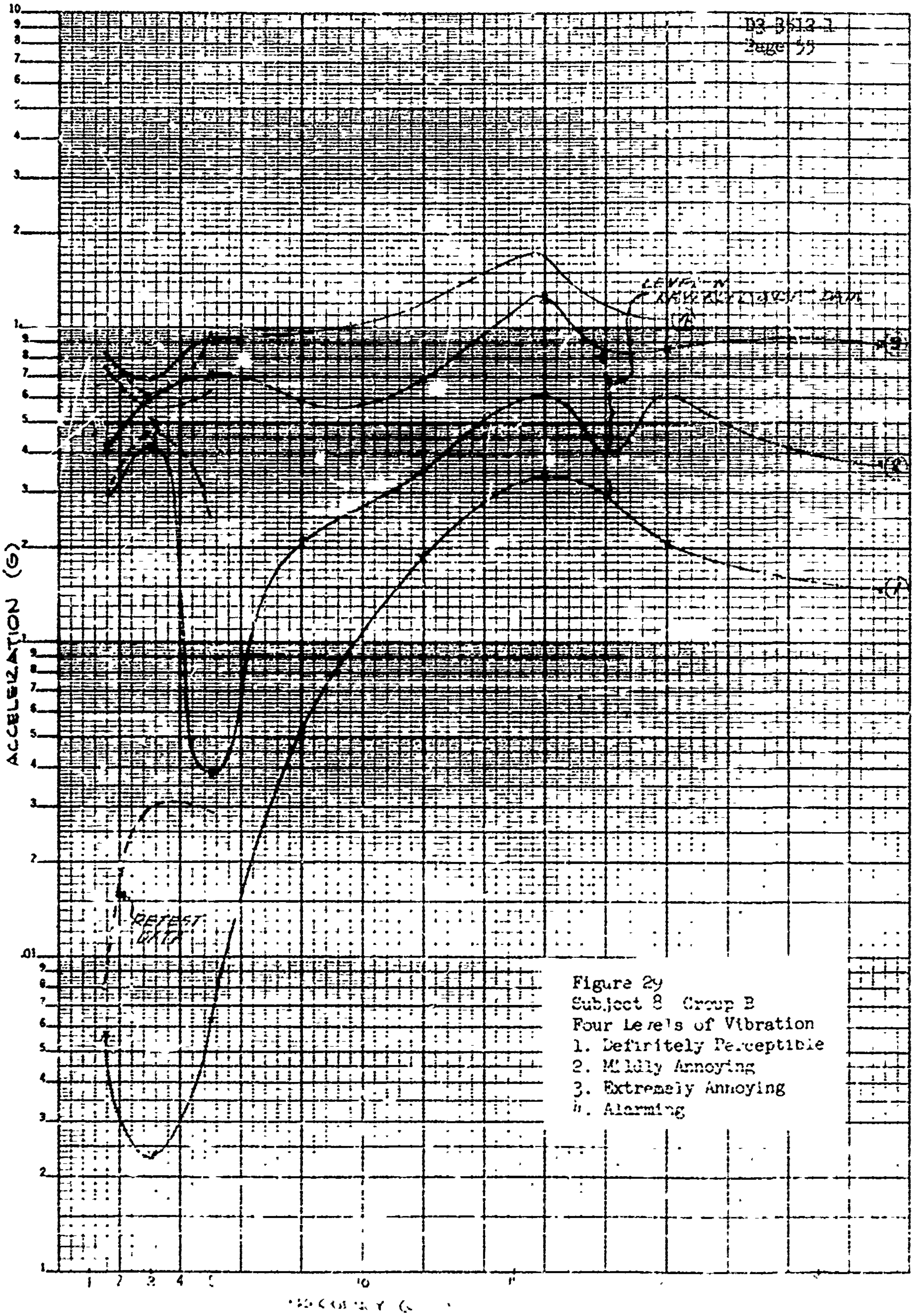


Figure 29
Subject 8 Group B
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

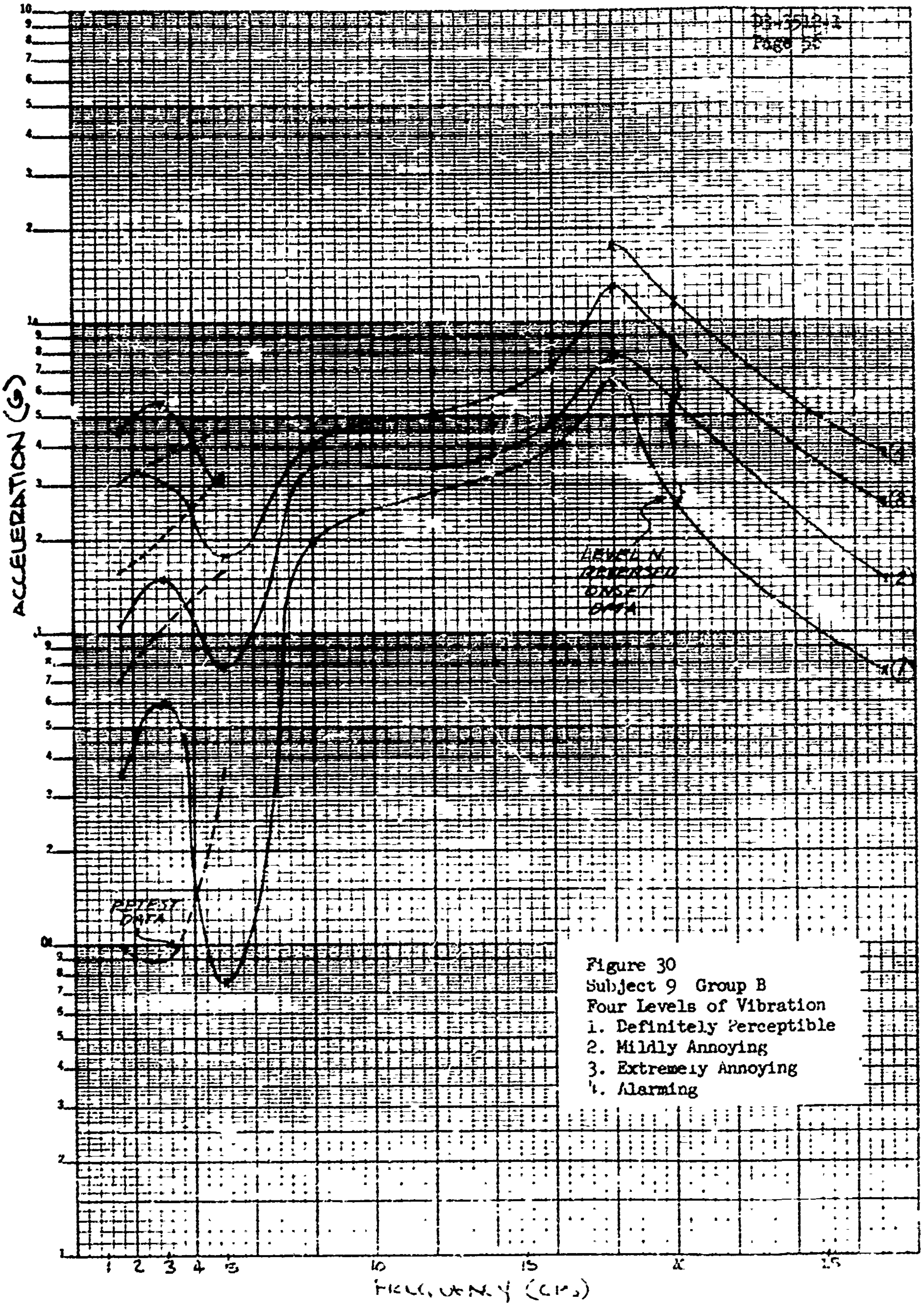


Figure 30
Subject 9 Group B
Four Levels of Vibration
1. Definitely Perceptible
2. Mildly Annoying
3. Extremely Annoying
4. Alarming

APPENDIX C

Selected references on human and animal response to the effects of low frequency vibration.

INTRODUCTION

There does not appear to be a comprehensive bibliography on vibration research. The ever increasing importance of problems resulting from vibration make it incumbent upon researchers in the area to add to the small and widely scattered partial bibliographies now extant. It is hoped that someday these will all be drawn together into a comprehensive whole. The following is not intended to be exhaustive even as far as whole body low frequency vibration is concerned. It is, as the title suggests, a selected list of references.

Many sources have been consulted in gathering these references. Bibliographic research has the character of an exponential progression; each item examined provides clues to many more items. The following listed items represent the major sources utilized in connection with a program of research supported, in part, by a contract with the Office of Naval Research (Nonr-2994-(00)).

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